Team Formation in a Network

Markus Kinateder*

Universitat Autònoma de Barcelona†

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Abstract

Two project leaders in a network, which captures social relations, recruit players in a strategic, competitive and time-limited process. Each team has an optimal size depending on the project's quality which is a random variable with a commonly known distribution. Only the corresponding project leader observes its realization. Any decision is only observed by the involved agents. A pure strategy Sequential Equilibrium exists under weak conditions. An agent's payoff is related to his position in the network, though no measure in the literature captures this relation. Hence, a way to identify the most central players is proposed. Due to the network's geography, inefficient unemployment may arise in equilibrium.

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1 Introduction

In this paper, the formation of start-up businesses is analyzed when entrepreneurs rely on their social or business contacts in the early process of founding a company. It is important

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†Departamento de Economía y de Historia Económica, Edificio B, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain; email: mkinateder@idea.uab.es

to understand this process better, to identify possible inefficiencies and to remove them. This would benefit economic growth which is fostered by entrepreneurs. They generate innovation and improve existing technologies. The economic literature on the impact of social networks in labor markets is surveyed by Ioannides and Loury (2004). However, to theoretically analyze an entrepreneur's recruitment in a network is novel.[1]

In reality, entrepreneurs need, apart from funding, to hire skilled and reliable people, such as friends, business contacts and relatives. Brüderl and Preisendörfer (1998) show empirically that entrepreneurs which start a business in the region in which they grew up obtain more and better support. Local networks and business connections significantly improve a start-up's success probability. This is due to better access to information, existing contacts with customers and suppliers, access to financing as well as due to an existing family and friends network which provides emotional support and unpaid work. Michelacci and Silva (2007) provide empirical evidence that locals have better access to funding and Blumberg and Pfann (2001) show that there is a positive relation between an individual's level of social capital and his decision to become self-employed.

Those which join the entrepreneur may recruit their friends or colleagues. The team's growth is restricted by the network which captures social relations, if it runs out of money (in this model there is a time limit), if there are no more individuals left to recruit or if the business idea is poor. Moreover, other teams may compete for the same individuals.

A stylized model is developed. It is dynamic, that is, the different stages of offers and replies are called time periods and a last period limits the game. The analysis focuses on two projects. The setup and each project's location are commonly known.[2] Each agent is either a player or a project leader. Each project leader knows his project's quality which influences the optimal number of contributors and each contributor's payoff, while the players only know the prior distribution of project qualities.

The group of players with the highest expected payoff is identified. Therefore, a unique Sequential Equilibrium is selected by letting the agents move sequentially and breaking any agent's indifference. To characterize the equilibrium is non-trivial since it depends on the network, the position of the projects and each player's position relative to them.

Inefficient unemployment may prevail in equilibrium. A reason for this is that players selfishly try to extract information about the more distant project's quality by waiting. The categorization of players according to their expected payoff before the game yields a

[1] That an agent is embedded in his socioeconomic environment was introduced by Granovetter (1985). The sociological analysis of entrepreneurship in networks was initiated by Aldrich and Zimmer (1986).

[2] As will be shown below, for the results obtained, it is sufficient that project leaders know their direct neighbors and players in which group or category they are.

new centrality measure which is unrelated with existing ones. In particular, it differs from Freeman's (1977) *betweeness* centrality and Burt's (1992) *structural holes*; information brokers bridge a structural hole between two groups of agents and benefit most from exchange between them. Example 2 illustrates the stark difference between the measures. Contrary to existing concepts in the literature, usually, a group of players is most central.

This paper is related with network formation games (see Jackson (2005) for a survey), in which the static equilibrium concept of pairwise stability is used. The analysis is usually less complex than in this model in which each agent's type and location matters. For example, Goyal and Vega-Redondo (2007) model a network formation game in which each pair of directly or indirectly linked players creates a surplus. However, intermediators on a path between two players pocket part of the surplus since they occupy a structural hole. The stable network is a star, or a circle if the players are restricted to form a limited number of links. Buskens and van der Rijt (2006) simulate a model in which every player strives to take such an intermediate position and find that balanced complete bipartite networks[3] obtain. They conclude that no agent can occupy a structural hole if everyone aspires to do so. The coalition formation literature uses similar ideas (see Ray (2008) for a survey). Each subset of players generates a value which is distributed among its members. A coalition is stable if none of its members wants to leave it and form a different one.

Bala and Goyal's (1998) model has similar features as the one in this paper. They study the relationship between network structure and social learning. Initially, players do not know which action yields the highest payoff. Over time they observe the outcome of their own and their neighbors' choices. This yields a dynamic learning process. As in this paper, players obtain information gradually over time and the informational restrictions are captured by a fixed network. In Stein (2008), every player has information which is only valuable together with that obtained from his neighbors. Hence, a player's relative position in the network matters. By communicating, underdeveloped ideas spread throughout the network while valuable ones remain local. Conversely, in this paper, high quality projects have the potential to spread further than those of low quality.

The game is defined in the next section. Two examples are provided in section 3. Section 4 contains the main results, namely equilibrium existence, the identification of the most central player(s) and several additional examples. A categorization of players based on the equilibrium is proposed. This yields a new centrality measure which is allocated to the network literature. Finally, the model's welfare implications are considered. Before concluding, various assumptions and possible extensions are discussed.

[3] In such a network, there are two (polarized) sides each with the same number of agents; each agent on one side is connected to all agents on the other side but not to any on his side.

2 Preliminaries

2.1 The Game in a Network

The agents in set $A = \{1, ..., n\}$, where $n > 2$ is finite, dispose of a set of projects denoted by $\mathcal{P} = \{1, 2\}$. The two project leaders, which take the first two positions in A, belong to set PL, while the agents which occupy positions 3 to n in A are players and belong to set I. Thus, $A = PL \cup I$. Let project leader 1 obtain project 1 and project leader 2 project 2.

Each agent has a fixed position in a network. Formally, the agents in A are the nodes of network η, whose graph is defined as the pair (A, E), where $E \subseteq A \times A$ denotes the set of links between them. A link from agent i to agent j is denoted by (i, j). Graph (A, E) is undirected: for all $i, j \in A$, $(i, j) \in E$ if, and only if, $(j, i) \in E$.

Given network η, a path between two distinct agents i and j is defined as a sequence of distinct agents $i_1, ..., i_r$ with $i_1 = i$, $i_r = j$, and $(i_{l-1}, i_l) \in E$, for all $1 < l \leq r$. Its length is $r - 1$. Network η is assumed to be connected. Hence, each agent is connected to at least one other agent directly and to all others via paths of finite lengths. The number of links along the shortest path between two distinct agents i and j is called *distance* between i and j. It is denoted by d_{ij}. The *largest distance* between agent i and any other agent in η is defined by $d_i = \max_{j \in A} d_{ij}$. Finally, denote agent i's set of direct neighbors by $i(1) = \{j \in A \mid d_{ij} = 1\}$, and for any $2 \leq m \leq d_i$, define his set of *m-neighbors* as $i(m) = \{j \in A \mid d_{ij} \leq m\}$. This set includes all agents at distance m or less from i.

The quality of each project $\gamma \in \mathcal{P}$ is denoted by $k_\gamma^q \in \mathbb{R}_+$, where $q \in \{L, H\}$ is *low* or *high* and obviously $k_\gamma^H > k_\gamma^L$.[4] Let $K_\gamma = \{k_\gamma^L, k_\gamma^H\}$ for any $\gamma \in \mathcal{P}$ and $K = \times_{\gamma \in \mathcal{P}} K_\gamma$. Each project's quality is randomly and independently drawn before the game begins. The outcome of each experiment is only observed by the corresponding project leader. For each $\gamma \in \mathcal{P}$, nature selects k_γ^H with probability $p_\gamma \in (0, 1)$ and k_γ^L with complementary probability $(1 - p_\gamma)$. The probabilities may vary across projects. Denote the commonly known vector of probabilities with which each project's quality is chosen to be high by $p = (p_1, p_2)$. Finally, let $k \in K$ be the vector of realized project qualities.

Following Harsanyi (1967-68), this game of incomplete information (about each project's quality, and as shown below, its payoff function) can be studied as one of imperfect information. By taking place in a network, the game becomes one of multiple stages called time periods. They are denoted by $t = 1, ..., T$, with $T \geq 1$ fixed exogenously. The fixed network η including each player's and project leader's position as well as the game's

[4] The extension of this setup to more than two quality levels is straightforward. However, for simplicity, the analysis will focus on the case of two quality levels per project.

setup are commonly known. Finally, let (η, T, K, p) be the game's tuple of parameters.

2.2 Strategies and History of the Game

Before the game begins, project leader $\gamma \in PL$ may reject his project. If he chooses to carry it out, at $t = 1$, γ may offer any neighbor except of project leader $3 - \gamma$, that is, any $j \in \gamma(1) \setminus \{3 - \gamma\}$ to join. Formally, γ's action at $t = 1$ is defined as $f_\gamma^1 \in \{\textit{offer}, \textit{no offer}\}^{\gamma(1)\setminus\{3-\gamma\}}$. Given f_γ^1, the set o_γ^1 of players which are offered to join project γ at $t = 1$ is determined. It is empty if γ does not issue any offer. Only a player who receives an offer observes it. He knows from which project it is but has no information about the project's quality or how many other players are offered to join it.

Each player $j \in o_\gamma^1$ decides whether to accept the offer or not. His action is defined as $g_j^1 \in \{\textit{Yes}, \textit{No}\}$ and is only observed by project leader γ. If player j receives offers from both projects at $t = 1$, his action is defined as $g_j^1 \in \{(\textit{Yes}, \textit{No}), (\textit{No}, \textit{Yes}), (\textit{No}, \textit{No})\}$, that is, he can at most join one project. If he receives no offer at $t = 1$, $g_j^1 = \emptyset$. After all players chose a (possibly "empty") action and the corresponding project leader(s) observed them, the second period starts. Each project leader may ask any unrecruited neighbor or a neighbor of a player who joined him at $t = 1$. This determines o_1^2 and o_2^2. In general, denote the set of players offered to join project γ at t by o_γ^t. Any unrecruited player who receives an offer decides whether to accept it or not. He does not know the project's quality, how many other players are offered to join it or joined it already and via which player(s) the offer is made, unless he can deduce this from the network's structure.

A player commits to a project forever—how to relax this assumption is discussed in section 5. Hence, if $\textit{Yes} \in g_j^s$ for any $s \geq 1$, player j cannot choose *Yes* any more at any t, where $s < t \leq T$. He rejects any offer from the other project leader and justifies his rejection—also if he receives two offers simultaneously.[5] A project leader may reissue his offer to any player which rejected it before, unless he knows that this player joined the other team already.[6] This yields a dynamic process of offers and replies.

Denote player i's private history at the end of period t by h_i^t. It contains every offer i received with his reply at all $1 \leq s \leq t$. A period's history in which he received no offer is empty. For any project leader $\gamma \in PL$ and any t, h_γ^t contains all offers γ made and the replies he received at all $1 \leq s \leq t$. Normalize any player i's and any project leader γ's history at the beginning of the game to $h_i^0 \equiv \emptyset$ and $h_\gamma^0 \equiv \emptyset$, respectively.

[5] A player's action space thus changes once he accepted an offer, though this is not modelled formally, nor is the justification the other project leader receives from a player who is not available any more.

[6] However, project leaders do not use offers to obtain information about the other project's quality. They simply intend to fill up their team on time.

Let F_γ denote the strategy set of any project leader $\gamma \in PL$. It contains all sequences of actions, called strategies, which γ may choose. Each is defined as $f_\gamma \equiv \{f_\gamma^t\}_{t=1}^T$, where f_γ^t is conditional on h_γ^{t-1} for any t. Let $F = \times_{\gamma \in PL} F_\gamma$ be the project leaders' strategy space with generic element f called (project leaders') strategy profile. Similarly, denote by G_i the strategy set of any player $i \in I$. Each element of this set is a sequence of actions, called strategy, which player i may choose. It is denoted by $g_i \equiv \{g_i^t\}_{t=1}^T$, where g_i^t is conditional on h_i^{t-1} and the offer(s) i receives at t. Let $G = \times_{i \in I} G_i$ be the players' strategy space with generic element g called (players') strategy profile. To emphasize player i's or project leader γ's role, g and f are written as (g_i, g_{-i}) and $(f_\gamma, f_{3-\gamma})$, respectively.

2.3 Payoff Function and Equilibrium Concept

Let b_γ denote the set of contributors of any project $\gamma \in \mathcal{P}$ and $|b_\gamma|$ its cardinality. Given γ's quality k_γ^q for $q \in \{L, H\}$, its leader calculates his optimal number of contributors $|b_\gamma^*(q)|$ by maximizing his project's payoff function $\pi^\gamma(|b_\gamma|, k_\gamma^q)$, which is assumed to be strictly concave in $|b_\gamma|$.[7] The solution is the lowest nonnegative integer for which the payoff is maximal given k_γ^q. The two projects' payoff functions are assumed to be identical. Since $k_\gamma^H > k_\gamma^L$, $|b_\gamma^*(H)| > |b_\gamma^*(L)|$ holds, unless both are zero. Finally, for a given positive number of contributors up to the optimal one, a high quality project yields its members a larger payoff than one of low quality.

Given f and g, project γ's actual set of contributors is $b_\gamma(f, g)$. It contains γ, unless it is empty since even γ does not contribute himself. Given $\pi^\gamma(|b_\gamma(f, g)|, k_\gamma^q)$ for $q \in \{L, H\}$, let $\pi_j^\gamma(|b_\gamma(f, g)|, k_\gamma^q) = \pi^\gamma(|b_\gamma(f, g)|, k_\gamma^q)/|b_\gamma(f, g)|$ be the realized payoff of any $j \in b_\gamma(f, g)$, that is, the contributors share their project's payoff equally. Agent j's payoff function maps $F \times G$ into $\mathbb{R}$. All agents observe their payoff only at the end of period T. Project leader γ's payoff is zero if $b_\gamma(f, g) = \emptyset$. Similarly, player i's payoff is zero if $i \notin \cup_{\gamma \in \mathcal{P}} b_\gamma(f, g)$.

At any $1 \leq t \leq T$, all agents use expected payoffs. To calculate them they form beliefs about each project's quality. When the game begins, player i's belief μ_i^0 is identical to the common prior p. Project leader γ's belief μ_γ^0 is identical to p as well except of its γth entry, which is 1 if γ's quality is high or 0 if it is low. If player i receives no new information before he moves at $1 \leq t \leq T$, his belief μ_i^t is identical to μ_i^{t-1}. He updates his belief from p_γ to 0 or 1 if, and only if, project γ's quality is revealed to him.[8] Hence, μ_i^t is an element of $\{0, p_1, 1\} \times \{0, p_2, 1\}$. It is uniquely determined given μ_i^{t-1}, h_i^{t-1} and the offer(s) i receives at t. Project leaders update beliefs analogously. Finally, let $\mu^t = \{\mu_1^t, ..., \mu_n^t\}$.

[7] Since γ contributes to his own project, he requires one player less than $|b_\gamma^*(q)|$ for $q \in \{L, H\}$.

[8] How agents deduce a project's quality is illustrated by examples in the next section.

For any t, given f, g and μ_γ^t, denote the payoff γ expects to receive at T by $\tilde{\pi}_\gamma^t(f,g)$. It is the weighted sum (by μ_γ^t) of his payoff at T in case project $3-\gamma$'s quality is low or high, respectively. A player's expected payoff after joining a project is calculated analogously if he knows its quality. Otherwise, he calculates his payoff at T for the four pairs of realized project qualities and weights them by his belief—in this case the prior. Any unrecruited player determines which project he may still join until T and his corresponding payoff, both conditional on the four pairs of realized project qualities. He then weights the four payoff functions by his belief. Denote any player i's expected payoff at any t by $\tilde{\pi}_i^t(f,g)$.

Define the Team Formation Game (TFG) as the tuple $((\eta, T, K, p), A, F, G, \tilde{\pi})$, where $\tilde{\pi} = (\tilde{\pi}_1^0(f,g), ..., \tilde{\pi}_n^0(f,g))$ and $\tilde{\pi}_j^0(f,g)$ is the expected payoff of agent $j \in A$ before the game begins. A Sequential Equilibrium (SE) strategy profile requires each agent to have an optimal action at any $1 \leq t \leq T$ given any history and his belief. In particular, the continuation strategy must be sequentially rational after any history for the remainder of the TFG. The system of beliefs consistent with the strategy profile is not defined formally since it is very simple: on a SE path, each agent at most updates his belief about each project's quality once.[9]

Definition 1. *Given any Team Formation Game $((\eta, T, K, p), A, F, G, \pi)$ and $\{\mu^t\}_{t=1}^T$, a Sequential Equilibrium is a pair of strategy profiles (f,g) such that at any $1 \leq t \leq T$,*

i) for all $\gamma \in PL$, h_γ^{t-1} and $\hat{f}_\gamma \in F_\gamma$, given k_γ^q for any $q \in \{L, H\}$,

$$\tilde{\pi}_\gamma^t(f,g) \geq \tilde{\pi}_\gamma^t(\hat{f}_\gamma, f_{3-\gamma}, g), \text{ and}$$

ii) for all $i \in I$, h_i^{t-1} and $\hat{g}_i \in G_i$,

$$\tilde{\pi}_i^t(f,g) \geq \tilde{\pi}_i^t(f, \hat{g}_i, g_{-i}) \text{ provided that Yes} \notin g_i^s \text{ for all } s < t.$$

After accepting an offer player i's strategy is trivial. As is shown below, a pure strategy SE exists in any TFG. It is found using *sequential rationality* (SR). At each $1 \leq t \leq T$, the agents move in increasing order of their indexes, that is, first project leaders 1 and 2, and then all players from 3 to n which are offered to join a project. Those which do not receive any offer, obviously, cannot take a decision. While the results are unchanged if project leaders move simultaneously, the sequentiality of the players' moves together with breaking any agent's indifference allows to select a unique SE, as is shown in section 4.

[9] At any t, the limit of a player's belief about project γ's quality is either 0, p_γ or 1. On an out of equilibrium path the same holds, but a player may have to update his belief more frequently, which causes no problem since in a SE each player always puts a positive belief on any history.

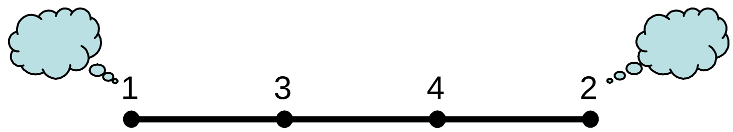

Figure 1: Four Players on a Line

3 Two Examples

3.1 Example 1: A Simple Coordination Game

Let $A = \{1, ..., 4\}$, where 1 and 2 are project leaders, and 3 and 4 are players, be organized on a line as depicted in Figure 1. Let $T = 2$, $k_\gamma^H = 1$, $k_\gamma^L = \frac{2}{3}$, $p_\gamma = \frac{1}{2}$ and $\pi^\gamma(|b_\gamma|, k_\gamma^q) = 3k_\gamma^q|b_\gamma| - \frac{1}{2}|b_\gamma|^2$ for $\gamma \in \mathcal{P}$ and $q \in \{L, H\}$;[10] hence, $|b_\gamma^*(H)| = 3$ and $|b_\gamma^*(L)| = 2$.

A player's decision at $T = 2$ is determined by SR. His belief is identical to the prior p, unless he is offered to join the more distant project and thus updates his belief about its quality to 1. If he receives two offers (since he did not join his project leader neighbor at $t = 1$ while the other player did) he joins the more distant (high quality) project, he accepts the single offer his project leader neighbor makes (since this yields him a higher payoff than his outside option of 0), or he cannot take any decision if he joined him already at $t = 1$ (apart from rejecting a second offer he may receive).

At $t = 1$, in a SE, each project leader offers his neighbor to join. Conditional on recruiting him, the project leader asks the other player at $T = 2$ if, and only if, his project's quality is high. At $t = 1$, the players *coordinate*[11] on one project, that is, one of them waits and the other accepts his neighbor's offer. The player which waits hopes to join the more distant project in case its quality is high. Otherwise, he can still join his project leader neighbor at $T = 2$. A player who joins a project at $t = 1$ hopes to recruit the other player in case the project's quality is high.

The player which waits obtains a higher expected payoff. With probability $\frac{1}{2}$ the more distant project's quality is high and the player's payoff is 4.5. With complementary probability of $\frac{1}{2}$, the player joins his project leader neighbor at $T = 2$. Since this project's quality is high or low with equal probability as well, the player obtains a payoff of 4 or 2, respectively, each with compound probability of $\frac{1}{4}$. Hence, a player's expected payoff from waiting is $\frac{1}{2}4.5 + \frac{1}{2}(\frac{1}{2}2 + \frac{1}{2}4) = \frac{15}{4}$ and it is $\frac{1}{2}2 + \frac{1}{2}4.5 = \frac{13}{4}$ if he accepts his offer at $t = 1$.

[10] Each player contributes 3 times the project quality units to the payoff of every $j \in b_\gamma$ and causes a cost, for example, due to the coordination effort, which increases exponentially in the number of contributors.

[11] In this paper, the expression *coordination* is used to describe a situation in which a group of players intends to join the same project even if some of them are closer to the other project.

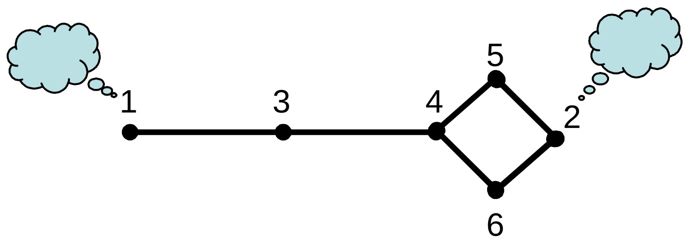

Figure 2: Network in example 2

A player which waits benefits from the other project if its quality is high. If it is not, he has a second chance to join a high quality project. In case either both players accept or reject their neighbors' offers at $t = 1$, both end up in different teams and obtain a lower expected payoff of $\frac{1}{2}2 + \frac{1}{2}4 = \frac{12}{4}$ in each case. In the unique SE, player 3 waits at $t = 1$ since waiting yields a higher payoff and he can choose to wait or not because he moves first. Player 4 joins project 2 at $t = 1$ by SR since he moves second. If project 2's quality is high, the teams $\{1\}, \{2, 3, 4\}$ form. Otherwise, the teams $\{1, 3\}, \{2, 4\}$ emerge: player 4 joins project 1 at $t = 1$ and player 3 project 2 at $T = 2$.

3.2 Example 2: The Illusion of Being most "Powerful"

Suppose that the agents in $A = \{1, ..., 6\}$ form the network depicted in Figure 2, that $k_\gamma^H = 2$, $k_\gamma^L = 1$ for $\gamma \in \mathcal{P}$ and $T = 3$; then, $|b_\gamma^*(H)| = 6$ and $|b_\gamma^*(L)| = 3$ given the same payoff function as in Example 1. At first sight, player 4 seems to get the highest expected payoff since he decides whether to join project 1 or 2. He is linked to three players and both project leaders may compete for him. He fills a structural hole and has the highest betweeness centrality (together with player 3) with respect to the two project leaders. Nevertheless, as is shown below, in the unique SE his expected payoff is lowest since players 3, 5 and 6 coordinate their behavior and thus take away player 4's power.

Given any quality level, project leader 1 needs to recruit at least two players. Hence, he offers player 3 and (if possible) 4 to join. Provided they join him on time, he asks players 5 and 6 if, and only if, project 1's quality is high. Project leader 2 tries to recruit all players as well if, and only if, project 2's quality is high. In case it is low, he only recruits players 5 and 6. Their strategies are symmetric if it is assumed that no player delays his decision out of indifference (see Assumption 1 in the next section). Player 4 is never asked to join project 2 if its quality is low. He updates his belief about its quality to 1 if, and only if, he receives an offer to join it which he accepts.

For player 3 to join project 1 at $t = 1$ strictly dominates to join it at $t = 2$ since he gives up his chance to join project 2 anyway but prevents project leader 1 from reaching players 5 and 6. Hence, he either joins it at $t = 1$ or decides at $T = 3$. In the first case, he hopes that project 1's quality is high and that players 5 and 6 are recruited; in the second, he hopes to join project 2 at $T = 3$, though he still may join project 1.

3.2.1 The Equal Likelihood Case

Thus far, the probability with which each project's quality is high did not matter. In order to proceed, let $p = (\frac{1}{2}, \frac{1}{2})$. Due to the network's geography, an offer from the more distant project leader may reach players 3, 5 and 6 only at $T = 3$. Each of them, provided he is still available, would accept it (since he updates his belief about the project's quality to 1). In case it is not made, the player accepts his project leader neighbor's offer at $T = 3$. The three players receive a higher expected payoff if they coordinate on one project. If player 3 joins project 1 at $t = 1$, players 5 and 6 decide only at $T = 3$. Conversely, if player 3 waits until $T = 3$, players 5 and 6, as assumed before, both join project 2 at $t = 1$. Hence, player 4 receives at most a single offer at $t = 2$ and accepts it in order to allow the corresponding project access to the player(s) on his other side.

Player 3's expected payoff in case he waits is 12.25 while player 4's is 8.75 and that of 5 and 6 is 11. Their expected payoff is 13.25 if they wait while that of 3 and 4 is 11. At $t = 1$, in the unique SE, player 3 waits since he moves first, and by SR, players 5 and 6 join project 2. Player 3 waits until he updated his belief about project 2's quality. If it is low, he can still join project 1. Player 4 is worst off in the SE since he remains unrecruited if project 2's quality is low.[12] Although, he fills a structural hole and has the highest betweeness centrality, in the unique SE, players 3, 5 and 6 "take away his power."

3.2.2 Changes in the Time Parameter and the Quality Probabilities

If $T > 3$, player 3 would wait until period $T - 1$ for an offer to join project 2. If it is not made, he joins project 1. This prevents players 5 and 6 from receiving project 1's offer.[13] By SR and since they do not delay their decision, they join project 2 at $t = 1$ (though they are indifferent to join it at any $1 \leq s \leq T - 3$). Player 4 joins project 2, if offered, at $t = 2$ and otherwise accepts project 1's offer at T. Player 3 joins project 2 at $t = 3$ if

[12] Even if the order of moves was reversed and players 5 and 6 waited at $t = 1$, while player 3 joined project 1, player 4 would not receive a higher expected payoff than any other player.

[13] If player 3 joined project 1 before $T - 1$, players 5 and 6 would wait to decide until project 1's quality is revealed to them. Obviously, this is not part of a SE.

offered and otherwise project 1 at $T-1$. Player 4's payoff then equals player 3's.[14]

Let $T=3$ again and consider changes in $\hat{p}=p_1=p_2$, the probability with which each project's quality is high. Denote by g' and g'' the players' strategy profiles in which they coordinate on project 1 and 2, respectively. Player 3 chooses to wait or not since he moves first, and players 5 and 6, by SR, join or wait, respectively. Player i's payoff if he joins project γ is $\pi_i^\gamma(|b_\gamma(f,g)|,k_\gamma^q)$ for $q\in\{L,H\}$ and $g\in\{g',g''\}$. The project leaders' strategy profile f is identical in both cases. Player 3 waits until $T=3$ if g'' is played and joins project 1 at $t=1$ under g'. Since he moves first, in the unique SE, he is better off to wait (since the other side joins) than to join (since the other side waits) if, and only if,

$$\hat{p}\ \pi_3^2(|b_2(f,g'')|,k_2^H)+(1-\hat{p})\ \hat{p}\ \pi_3^1(|b_1(f,g'')|,k_1^H)+(1-\hat{p})\ (1-\hat{p})\ \pi_3^1(|b_1(f,g'')|,k_1^L)\geq$$

$$\hat{p}\ \pi_3^1(|b_1(f,g')|,k_1^H)+(1-\hat{p})\ \pi_3^1(|b_1(f,g')|,k_1^L).$$

Obviously, $\hat{p}\pi_i^1(|b_1(f,g')|,k_1^H)=\hat{p}\pi_i^2(|b_2(f,g'')|,k_2^H)$ for all $i\in I$ and it cancels on both sides. Then, $(1-\hat{p})$ drops out of the inequality as well. This yields

$$\hat{p}\ \pi_3^1(|b_1(f,g'')|,k_1^H)+(1-\hat{p})\ \pi_3^1(|b_1(f,g'')|,k_1^L)\ \ \geq\ \ \pi_3^1(|b_1(f,g')|,k_1^L),$$

and thus,

$$\hat{p}\geq\frac{\pi_3^1(|b_1(f,g')|,k_1^L)-\pi_3^1(|b_1(f,g'')|,k_1^L)}{\pi_3^1(|b_1(f,g'')|,k_1^H)-\pi_3^1(|b_1(f,g'')|,k_1^L)}. \tag{1}$$

Note that the numerator and denominator of (1) are nonnegative. This equation is derived in a general way since it holds analogously for players 5 and 6 (however, substituting the players' and projects' indexes, g' with g'' and vice versa). Using (1), the range of $\hat{p}$ can be calculated for which each side prefers to wait if the other side joins. For player 3 the threshold value of $\hat{p}$ is $\frac{4.5-4}{10-4}=\frac{1}{12}$ and it is $\frac{4.5-4.5}{13-4.5}=0$ for players 5 and 6. For $\hat{p}\in(0,\frac{1}{12})$, in the unique SE, player 3 prefers to join project 1 at $t=1$, while for all larger values of $\hat{p}$ he waits. Since $\hat{p}$ is larger than zero, players 5 and 6 always prefer to wait rather than to join project 2 at $t=1$, though they best-reply to player 3's choice since he moves first.[15] Moreover, both sides never wait or join simultaneously for any $\hat{p}\in(0,1)$.

[14] If player 3 joins project 1 only at T, his expected payoff would be larger than player 4's. This might be better for player 3, for example, if the players' relative payoff ranking matters.

[15] If players 5 and 6 moved first, they would wait and player 3 would join project 1 at $t=1$. At $T=3$, players 5 and 6 by joining project 2 form a three-agent team while player 3 would be left with project leader 1 only. Hence, for $\hat{p}\in(0,\frac{1}{12})$, he joins project 1 at $t=1$ and player 4 is recruited at $t=2$.

4 Equilibrium in any Team Formation Game

Although the fixed order of moves eliminates many equilibria, frequently, the agents out of indifference have various possible equilibrium strategies. In order to select a unique SE, two more assumptions are made. Assumption 1 ($A1$) states that no agent "unnecessarily" delays his decision and was already introduced in Example 2.

Assumption 1. *A player which at most receives one offer (possibly from some point in time on) immediately accepts it. A project leader recruits in a circular cascade, if possible.*

The behavior implied by $A1$ arises in a SE if there is a small waiting cost, each agent's payoff is discounted over time, or T is a random variable and with a small probability any period before T is the last one. $A1$ implies that a project leader offers any player to join which previously was not accessible until his project is filled or T is reached and imposes players not to delay their decision out of indifference to join a project now or later.

Given $A1$, suppose that at a distance up to T from each project there are less or just enough players to fill it if its quality is low and that no player is competed for by both. Then, each agent's SE strategy is unique as is shown in Proposition 1.

Proposition 1. *Given any TFG, suppose that $A1$ holds. Then, there is a unique SE $(\dot{f}, \dot{g})$, if $|\gamma(T)| \leq |b^*_\gamma(L)| - 1$ for all $\gamma \in PL$ and $1(T) \cap 2(T) = \emptyset$.*

Proof. Given any TFG, suppose that $A1$ holds, and assume that $|\gamma(T)| \leq |b^*_\gamma(L)| - 1$ for all $\gamma \in PL$ and that $1(T) \cap 2(T) = \emptyset$. Then, each project leader γ's optimal strategy $\dot{f}_\gamma$ is to recruit in a circular cascade, that is, at $t = 1$ he asks his direct neighbors, conditional on receiving positive answers, at $t = 2$, he asks his second-neighbors and so on. Finally, at T he offers all players at distance T from him to join (conditional on having recruited all closer players before). Each player $i \in I$ receives at most one offer since $1(T) \cap 2(T) = \emptyset$. His optimal strategy $\dot{g}_i$ is to accept it immediately. $A1$ ensures uniqueness since project leaders and players do not delay their decision. □

If $A1$ does not hold, a unique SE obtains under all other conditions in Proposition 1 only if the agents form a tree, a circle or a line. Otherwise, more equilibria arise if a player, by delaying his decision to join a project, does not obstruct its leader's access to players at a larger distance. Similarly, a project leader could initially bypass a player if this does not prevent his access to players at a larger distance. If he recruits all bypassed players on time, this is a SE ruled out by $A1$.

If $|b^*_\gamma(H)| - 1 \leq |\gamma(T)|$, but all other conditions in Proposition 1 hold, project leader γ's strategy need not be unique. At each distance there are either less, more or just enough players such that together with all players at all lower distances his project is filled. If at some distance there are just enough players to fill it, uniqueness obtains under $A1$ which prescribes project leaders to recruit closer players before more distant ones. However, should a project leader reach a distance at which there are more players to fill his project, then he is indifferent which to ask. Each would accept his offer since the other project is too far away (that is, since $1(T) \cap 2(T) = \emptyset$). In this case, Assumption 2 ($A2$) applies.

Assumption 2. *A player which is indifferent between two projects joins (or aspires to join) the lower indexed project. In case of being indifferent, project leader 1 asks lower indexed players and project leader 2 higher indexed players.*

$A2$ is a selection criterion that breaks a player's or project leader's indifference in case he has various payoff-equivalent options. The corresponding behavior arises endogenously if agents have lexicographic preferences over all teams that may form in case of being indifferent.[16] An immediate corollary of Proposition 1 and the discussion thereafter is that there is a unique SE as long as $A1$ and $A2$ hold and provided that $1(T) \cap 2(T) = \emptyset$.

Corollary 1. *Given any TFG, suppose that $A1$ and $A2$ hold. Then, there is a unique SE $(\tilde{f}, \tilde{g})$, if $1(T) \cap 2(T) = \emptyset$.*

The assumption that projects do not compete for players, made in Proposition 1 and Corollary 1, need not hold, such as in Examples 1 and 2. A project leader's SE strategy given $A1$ and $A2$ in case $1(T) \cap 2(T) \neq \emptyset$ and $o_1^t \cap o_2^t \neq \emptyset$ for some $1 \leq t \leq T$ is strictly dominant and the players' best-reply is unique as is shown in Proposition 2.

Proposition 2. *Given any TFG, suppose that $A1$ and $A2$ hold. Then, there is a unique SE (f^*, g^*).*

Proof. The proof is divided in two parts. Part I shows that each project leader γ has a strictly dominant strategy $f_\gamma^* \in F_\gamma$, provided that $A1$ and $A2$ hold. Part II shows that the players' best-reply $g^* \in G$ is unique. Together this yields the unique SE.

Part I. Given any TFG, suppose that $A1$ and $A2$ hold. Then, project leader γ's strictly dominant strategy given $|b_\gamma^*(q)|$, for $q \in \{L, H\}$, is as follows. By $A1$, γ offers any player he can access to join unless T is reached, his project is filled or all accessible players join(ed) project $3 - \gamma$. By $A2$, γ uniquely selects the players to ask if he can access more than required and he is indifferent which to ask. If γ is not indifferent since a player rejects his offer in order to wait for another one by project leader $3 - \gamma$, γ does not reissue his offer

[16] Alternatively, suppose that the agents are anonymous. Then, $A2$ states that equilibrium multiplicity that can be reduced by relabelling players' names or indexes is ignored.

to this player if, and only if, the player may reject it again and γ can access enough other players to fill his project which (he believes will) accept his offer. Finally, $A1$ implies that a project leader never resumes to issue offers once he stopped. This yields $f^* \in F$.

Part II. Given $f^* \in F$, at any t, the set of unrecruited players is partitioned in categories 0, 1 and 2 as follows. Players in category 0 never receive an offer. Players in category 1 may at most receive one offer and players in category 2 may still receive offers from both projects. At any s, where $t < s \leq T$, the groups' composition may change after the players receive offers and update their beliefs. A player stays in the same category or drops to a lower-indexed one. Players which accept an offer are not categorized any more.

Players in category 0 never take a decision. By $A1$, those in category 1 immediately accept the only offer they may receive. The players in category 2 closest to each of the two projects calculate their expected payoff of waiting and joining (given that the other side waits or joins, respectively). The players coordinate on one project if one side waits and the other joins. If both join, the players one distance further away from each project calculate their expected payoff and decide whether to join or to wait given the other group's behavior. Both groups may wait for some time until at least one project's quality is revealed to them. A player's indifference to wait or to join is broken by $A2$.

A player drops from category 2 to category 1 if he loses the option to join one of the two projects, either because it is too far away to reach him on time or because he updates his belief about its quality to 0. Similarly, a player may drop to category 0. □

For any TFG, the players can be categorized at any t, taking into account their position in η relative to that of project leaders 1 and 2 and each agent's equilibrium strategy. This categorization is unique since there is a one to one correspondence with the SE.

Corollary 2. *Given any TFG, suppose that $A1$ and $A2$ hold. Then, at any $1 \leq t \leq T$, each player $i \in I$ is uniquely allocated to one category given the unique SE (f^*, g^*).*

Proposition 3 shows how to derive the different categories before the game begins, provided $A1$ and $A2$ hold, and given the unique SE (f^*, g^*). This is the basis to identify a new centrality measure, as shown in the next subsection.

Proposition 3. *Given any TFG, suppose that $A1$ and $A2$ hold. Then, the categories before the game begins can be uniquely identified, given the unique SE (f^*, g^*).*

Proof. Given any TFG, suppose that $A1$ and $A2$ hold. Find the unique SE (f^*, g^*). Since the players do not know the realized project qualities when the game begins, for every $k \in K$, the corresponding equilibrium path is derived. Each player which may never

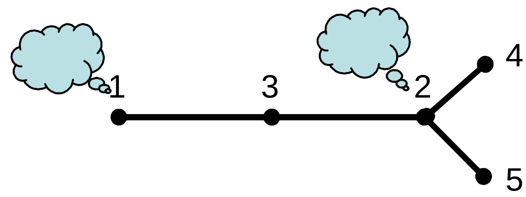

Figure 3: A Tree with Origin in Project Leader 2

join a project is allocated to category 0, denoted by $\mathcal{C}_0^0$. A player which may join both projects, possibly in different realizations of the project qualities, is allocated to category 2, denoted by $\mathcal{C}_2^0$. All other players belong to category 1, denoted by $\mathcal{C}_1^0$. $\square$

Since for $k = (k_1^H, k_2^H)$, the projects' extension is largest, this case serves to identify a subset of the competed for players in $\mathcal{C}_2^0$. Each project leader $\gamma \in PL$ counts the players at distance 1, 2 and so on from him until they fill his project if its quality is high. Formally, given $|b_\gamma^*(H)|$, for each $\gamma \in PL$ let distance m_γ be such that $|\gamma(m_\gamma)| \geq |b_\gamma^*(H)| - 1$, but $|\gamma(m_\gamma - 1)| < |b_\gamma^*(H)| - 1$ without taking into account paths that include project leader $3 - \gamma$. Distance m_γ is project leader γ's largest distance if there are not more players than $|b_\gamma^*(H)| - 1$ in the network and $3 - \gamma$ does not obstruct his access to any of them. In Figure 3, for example, $m_1 = 1$ since project leader 1 can only access player 3. If $|\gamma(m_\gamma)| > |b_\gamma^*(H)| - 1$, project leader γ selects the players at distance m_γ by $A2$. Since the recruitment is time constrained, that is, T may be smaller than m_γ, let $\hat{m}_\gamma = \min\{T, m_\gamma\}$.

Slightly abusing notation, denote the set of players project leader γ would like to ask if project γ's quality is high by $\gamma(\hat{m}_\gamma(H))$. Any player in this set expects to receive γ's offer with positive probability before the game begins. Analogously, allocate all players which fill γ if its quality is low to $\gamma(\hat{m}_\gamma(L))$, again abusing notation. This set is a strict subset of $\gamma(\hat{m}_\gamma(H))$, unless T limits γ's recruitment or he cannot access enough players. Players in the intersection of $1(\hat{m}_1(H))$ and $2(\hat{m}_2(H))$ expect to receive offers from both projects before the game begins and are allocated to a subset of $\mathcal{C}_2^0$, namely to

$$\mathcal{C}_{2.1}^0 = \{i \in I \mid i \in 1(\hat{m}_1(H)) \cap 2(\hat{m}_2(H))\}.$$

The SE is trivial if $\mathcal{C}_{2.1}^0 = \emptyset$. Then, Corollary 1 holds and $\mathcal{C}_2^0 = \emptyset$. Each player receives at most one offer and accepts it immediately. If each project's quality is high and $\mathcal{C}_{2.1}^0 \neq \emptyset$, there are not enough players in sets $1(\hat{m}_1(H))$ and $2(\hat{m}_2(H))$ to fill both of them and at least one project leader needs to ask more distant players, provided he can access them on time. Therefore, category $\mathcal{C}_2^0$ may contain more players than those in $\mathcal{C}_{2.1}^0$. The players in $\mathcal{C}^0_{2.1}$ "closest" to each project are called barrier players since they (may have to) decide whether a project leader gains access to the players in $\mathcal{C}^0_{2.1}$ and thus (may) constitute a barrier for him. For each $\gamma \in \mathcal{P}$, define the set of barrier players as

$$BP_\gamma = \{i \in \mathcal{C}^0_{2.1} \mid d_{\gamma i} = 1 \text{ or } d_{\gamma i} = d_{\gamma j} + 1 \text{ for some } j \in i(1) \text{ s.t. } j \in I \setminus \mathcal{C}^0_{2.1}\}.$$

Unless BP_γ is a singleton, $d_{\gamma i} \neq d_{\gamma i'}$ may hold for $i, i' \in BP_\gamma$. One project leader may reach his barrier player(s) faster than the other. All players in η belong to $\mathcal{C}^0_2 \equiv \mathcal{C}^0_{2.1}$ if $|I| \leq \min_{\gamma \in PL} |b^*_\gamma(H)|$, $m_\gamma \leq T$, and both project leaders can access all players. Then, as in Examples 1 and 2, each project leader's barrier players are his neighbors.

To provide an algorithm for the categorization at any $1 \leq t \leq T$ is involved and does not yield additional insights. In general, the players need not coordinate on one project (immediately), and hence, anything may occur. This is illustrated in Example 3 below. Other examples of the categorization and the unique SE are given in section 4.2.

4.1 A New Centrality Measure

In this subsection, the players with the highest (ex ante) expected payoff are identified.

Definition 2. *Given any TFG, suppose that A1 and A2 hold. Any player $i \in I$ with the highest (ex ante) expected payoff is said to be* most central.

Frequently, several players are most central. Other centrality measures also identify groups to be most central, but as in Ballester et al. (2005) the size of the group usually is fixed exogenously before its members are determined. In Wasserman and Faust (1994), chapter 5, it is shown how various measures which identify a single most central player extend to group centrality. In this model, the size of the group is determined endogenously by selecting all players with the highest expected payoff given the unique SE (f^*, g^*).

If the players coordinate on one project, their expected payoff can be easily calculated and compared, and thus the most central players identified. Otherwise, this is more involved since the most central players may belong to different categories at the beginning of the game. Obviously, players in category 0 are not most central.

Suppose that the players coordinate on project 1 and project 2's barrier players wait until project 1's quality is revealed to them. (In case the players coordinate on project 2 just relabel the projects' indexes.) The expected payoff of any $j \in BP_2$ in this case is

$$p_1\ \pi^1_j(b_1(f^*, g^*), k^H_1) + (1 - p_1)\ [p_2\ \pi^2_j(b_2(f^*, g^*), k^H_2) + (1 - p_2)\ \pi^2_j(b_2(f^*, g^*), k^L_2)]. \quad (2)$$

If $\pi_j^2(b_2(f^*, g^*), k_2^L) \neq 0$, the players in BP_2 which join project 2 even if both projects' quality is low have a larger expected payoff than any player i who joins project 2 (and only receives the second term $p_2\ \pi_i^2(b_2(f^*, g^*), k_2^H) + (1-p_2)\ \pi_i^2(b_2(f^*, g^*), k_2^L)$ as expected payoff). Any player $i \in 1(\hat{m}_1(L))$ receives an expected payoff of $p_1\ \pi_i^1(b_1(f^*, g^*), k_1^H) + (1-p_1)\ \pi_i^1(b_1(f^*, g^*), k_1^L)$. This is strictly smaller than the expected payoff of any player $j \in BP_2$, who joins project 2 unless project 1's quality is high, if

$$\pi_i^1(b_1(f^*, g^*), k_1^L) < p_2\ \pi_j^2(b_2(f^*, g^*), k_2^H) + (1-p_2)\ \pi_j^2(b_2(f^*, g^*), k_2^L).$$

All barrier players of project 2 for which this conditions holds have the highest expected payoff. If the inequality is reversed, any player $i \in 1(\hat{m}_1(L))$ has the highest expected payoff and if it holds with equality, both groups of players are most central.

If $\pi_j^2(b_2(f^*, g^*), k_2^L) = 0$ in (2), the players in BP_2 are recruited only if at least one project's quality is high, and their expected payoff is $p_1\ \pi_j^1(b_1(f^*, g^*), k_1^H) + (1-p_1)\ p_2\ \pi_j^2(b_2(f^*, g^*), k_2^H)$. For any $\gamma \in \mathcal{P}$, any player $i \in \gamma(\hat{m}_\gamma(L))$ has an expected payoff of $p_\gamma\ \pi_i^\gamma(b_\gamma(f^*, g^*), k_\gamma^H) + (1-p_\gamma)\ \pi_i^\gamma(b_\gamma(f^*, g^*), k_\gamma^L)$. Any player which only expects to join a project in case its quality is high receives only the first term. Again, the players whose expected payoff is largest are identified.

In general, the barrier players may not coordinate on a project or only after for some time, as illustrated in Example 3 below. Henceforth, the analysis is not always as simple as suggested here. This centrality measure's predictions are derived for various examples next and compared with those of existing concepts in the literature in section 4.3.

4.2 Examples of the Categorization

In various examples, the categorization of players before the game begins is illustrated and the most central players are identified. Therefore, the unique SE is obtained.

4.2.1 Example 3: The optimal strategy of barrier players

This example illustrates two important issues. First, both groups of barrier players might not wait for an offer from the more distant project, that is, coordination does not take place. Second, both groups of barrier players might wait (at least for some time).

Consider first the network depicted in Figure 4. Let $T = 3$, $p_1 = p_2 = \frac{1}{3}$, $k_\gamma^H = \frac{5}{3}$ and $k_\gamma^L = 1$ for $\gamma \in \mathcal{P}$. Given the same payoff function as in Example 1, $|b_\gamma^*(H)| = 5$ and $|b_\gamma^*(L)| = 3$. Players 3 to 6 and 9 to 12 can only receive one offer and accept it immediately; they belong to $\mathcal{C}_1^0$. Barrier players 7 and 8 belong to $\mathcal{C}_2^0 \equiv \mathcal{C}_{2.1}^0$. Only player 7's strategy

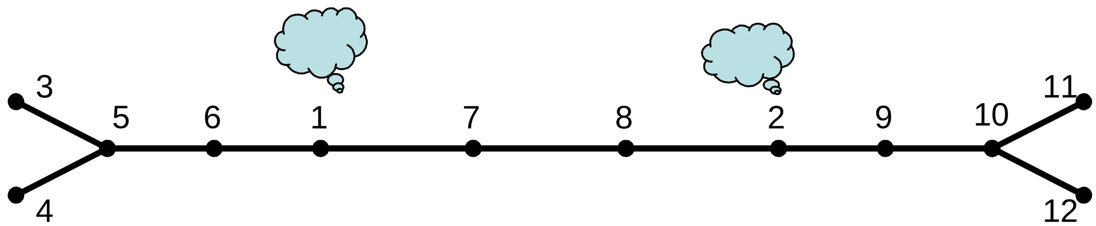

Figure 4: Both groups of Barrier Players do not wait

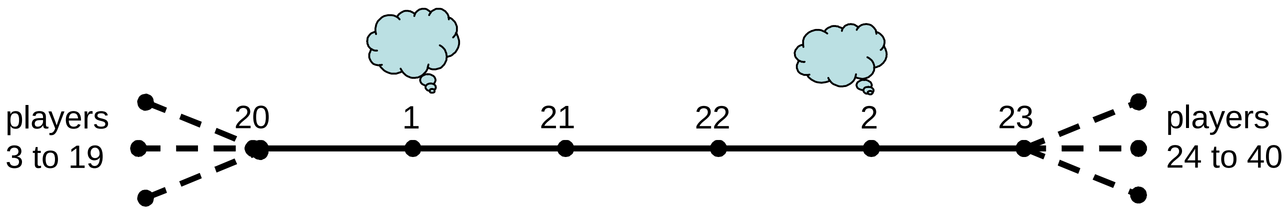

Figure 5: Both groups of Barrier Players wait initially

is analyzed since their position is symmetric. In case he joins project 1 at $t = 1$, his expected payoff is $\frac{2}{3}4.5 + \frac{1}{3}12.5 = 7\frac{1}{6}$. If he waits until $t = 2$, he is offered to join project 1 again if, and only if, its quality is high. (Otherwise, project leader 1 asks player 5.) If the players coordinate on project 2, player 7 receives an offer to join it at $t = 2$ if, and only if, its quality is high. His expected payoff in this case is $\frac{1}{3}12.5 + \frac{2}{3}(\frac{1}{3}12.5 + \frac{2}{3}0) = 6\frac{17}{18}$. Hence, at $t = 1$, player 7 is better off to join project 1 and player 8 project 2. Players 6 to 9 receive an expected payoff of $7\frac{1}{6}$ and are most central.

Consider next the network depicted in Figure 5. Let $T = 4$, $p_1 = p_2 = \frac{9}{10}$, $k_\gamma^H = 7$ and $k_\gamma^L = 1$ for $\gamma \in \mathcal{P}$. Given the same payoff function as in Example 1, $|b_\gamma^*(H)| = 21$ and $|b_\gamma^*(L)| = 3$. Again, only the strategy of barrier players 21 and 22 is interesting. Since their position is symmetric, only player 21's strategy is analyzed. By $A1$, he is asked to join project 1 at $t = 1$ in any case. This offer is repeated at $t = 2$ if, and only if, project 1's quality is high. (If it is low, by $A2$, its leader asks player 3.) Analogously, this holds for player 22 as well. Both would like to join the same high quality project. Since they wait at $t = 1$, they coordinate on a project after updating their beliefs at $t = 2$. Player 21 joins project 1 then if offered. Player 22 accepts project leader 1's offer at $t = 3$ or otherwise joins project 2 if offered. Player 21 could then be included in project 2 at $T = 4$.

A barrier player's expected payoff from joining his project leader neighbor at $t = 1$ is $\frac{1}{10}4.5 + \frac{9}{10}220.5 = 198.9$, provided the other barrier player joins it as well. In case both of them wait until the projects' qualities are revealed to them, both join the same high

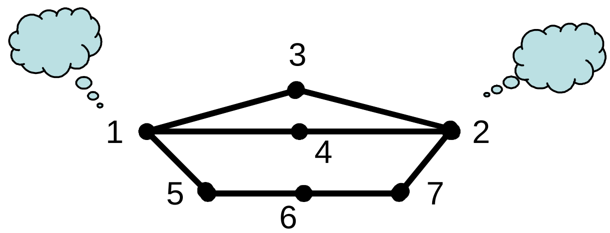

Figure 6: The "boiling soup pot"

quality project with probability 0.99 and receive a payoff of 0 with probability 0.01. Their expected payoff in this case is 218.295 which is strictly larger than 198.9. Since no other player has the option to join both projects, the two barrier players are most central.

4.2.2 Example 4: The "boiling soup pot"

In the network depicted in Figure 6, assumption $A2$ breaks the symmetry between players 3 and 4 and makes player 4 the most central player. Let $T = 2$, $p_1 = p_2$, $|b^*_\gamma(H)| = 4$ and $|b^*_\gamma(L)| = 3$ for $\gamma \in PL$. Then, $\hat{m}_\gamma = 1$ for $\gamma \in PL$ and players 3 and 4 belong to $\mathcal{C}^0_{2.1}$. They are the only barrier players in the network. However, player 6 belongs to $\mathcal{C}^0_2$ as well since he may receive an offer to join both projects while players 5 and 7 belong to $\mathcal{C}^0_1$.

At $t = 1$, by $A2$, project leader 1 asks player 3 among the barrier players and player 5 who is not competed for. He additionally offers player 4 to join if, and only if, project 1's quality is high. Similarly, project leader 2 asks players 4 (by $A2$) and 7, and additionally 3 if, and only if, project 2's quality is high. Players 5 and 7 accept their offers. Player 3 would join project 2 and player 4 project 1 since this reveals them the corresponding project's high quality. Each of them joins the other project if this offer is not made.

The teams $\{1, 3, 5\}$ and $\{2, 4, 7\}$ form if both projects' quality is low. If project 1's quality is high and project 2's is low, project 1 fills at $t = 1$ with players 3, 4 and 5, while project leader 2 recruits player 7 at $t = 1$ and player 6 at $T = 2$. The teams $\{1, 3, 4, 5\}$ and $\{2, 6, 7\}$ form. If project 2's quality is high and project 1's low, project 2 fills at $t = 1$ with players 3, 4 and 7, while project leader 1 recruits player 5 at $t = 1$ and player 6 at $T = 2$. The teams $\{1, 5, 6\}$ and $\{2, 3, 4, 7\}$ form. Finally, if both projects' quality is high, the teams at $t = 1$ are $\{1, 4, 5\}$ and $\{2, 3, 7\}$. Both leaders offer player 6 to join at $T = 2$. Since he only receives two offers in this case, he updates his belief about both projects' quality to 1. By $A2$, he joins project 1.

The most central player is identified even without specifying the form of the payoff function and $p_1 = p_2$. Only player 4 is included in each high quality team of size four which

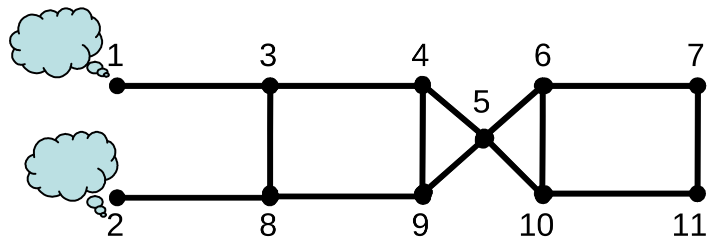

Figure 7: A Ladder with one Rung substituted by a Cross

forms and he belongs to a low quality team of size three when both projects' quality is low. Hence, no other player's expected payoff is higher than his and he is most central. Player 3 whose position seems to be symmetric to player 4's has a lower expected payoff since player 6, by $A2$, joins project 1 in case both projects' quality is high.

4.2.3 Example 5: Restricted access

In the network depicted in Figure 7, the project leaders are on one side and the players on the other. Hence, inefficient unemployment may obtain in the SE, as is discussed in more detail in section 4.4. Suppose that $T = 5$, $p_1 = p_2$, $|b^*_\gamma(H)| = 6$ and $|b^*_\gamma(L)| = 3$ for $\gamma \in PL$. Then, $\hat{m}_\gamma = 3$ for $\gamma \in PL$ and $\mathcal{C}^0_{2.1} = \{3, 4, 5, 8, 9\}$ with $BP_1 = \{3\}$ and $BP_2 = \{8\}$. Players 3 and 8 would prefer to wait until they knew the more distant project's quality. However, since player 3 moves first, he waits at $t = 1$, and player 8 joins project 2 by SR and $A1$. At $t = 2$, project 2 includes player 9 (by $A2$) if its quality is low. If it is high, its leader additionally recruits player 3, who updates his belief about its quality to 1, and thereafter, players 4 and 5. If it is low, project leader 1 recruits players 3 and 4, and additionally 5, 6 and 10 if, and only if, project 1's quality is high.

At $t = 3$, player 4 is offered to join either project 2 together with player 5 or project 1. In the first case, players 4 and 5 update their beliefs about project 2's quality to 1 and in the second to 0. At $t = 4$, player 5 then joins project 1 if its quality is high, or updates his belief about its quality to 0. At $T = 5$, players 6 and 10 either join project 1 or remain unrecruited. However, they cannot distinguish the case in which both projects' quality is low from the one in which project 2's quality is high. Hence, they update their beliefs about the two projects' qualities only if they are offered to join project 1.

Players 6 and 10 belong to $\mathcal{C}^0_1$ and players 7 and 11, throughout the game, to category 0. Teams $\{2, 3, 4, 5, 8, 9\}$ and $\{1\}$ form if project 2's quality is high (independently of project 1's quality); teams $\{2, 8, 9\}$ and $\{1, 3, 4\}$ form if both projects' quality is low and teams $\{2, 8, 9\}$ and $\{1, 3, 4, 5, 6, 10\}$ arise if project 1's quality is high and project 2's low.

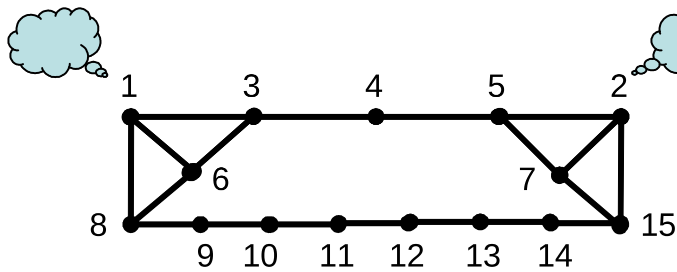

Figure 8: The SE depends on p

Players 3 and 4 are most central. They join any high quality project which forms and in case there is none they are included in low quality project 1.

Suppose now that $6 > |b^*_\gamma(L)| > 3$ and $p_1 = p_2$. If player 3 waits at $t = 1$, he is offered to join project 2 at $t = 2$ in any case. If he rejects this offer, he risks to be left out of a low quality project 2 and is left with project leader 1 only. Hence, it is not profitable for him to wait until project 2's quality is revealed and, by $A2$, he joins project 1 at $t = 1$. Player 8 rejects project leader 2's offer at $t = 1$ by SR and joins project 1 at $t = 2$ together with player 4. At $3 \leq t \leq T$, project leader 1 may ask more players. Project leader 2 is the only contributor of his project. Players 6, 7, 10 and 11 are allocated to category 0 throughout the game. All other players belong to $\mathcal{C}^0_1$, and all players which join project 1 even if its quality is high are most central.

4.2.4 Example 6: The SE depends on p

To find the SE might be more complex, as illustrated for the network depicted in Figure 8. Let $T = 5$, $p_1 = p_2 = \dot{p}$, $|b^*_\gamma(H)| = 10$ and $|b^*_\gamma(L)| = 7$ for $\gamma \in PL$. Then, $\hat{m}_\gamma = 4$ and the leader of high quality project 1 aims to recruit players 3 to 11 and that of high quality project 2 players 3 to 7 and 12 to 15. Hence, $\mathcal{C}^0_{2.1} = \{3, 4, 5, 6, 7\}$, $BP_1 = \{3, 6\}$ and $BP_2 = \{5, 7\}$. Both groups of barrier players prefer to wait until they know the more distant project's quality. Since player 3 moves first, he might wait for project 2's offer until $T = 5$, and then, if it is not made, join project 1. Since by $A1$ no agent delays his decision unnecessarily, he might have to join it already at $t = 3$, unless he is asked to join project 2 by then. However, players 4 and 5 might then wait until project 1's quality is revealed to them. Thus, the SE depends on the value of $\dot{p}$ and three cases may occur.
Case 1: Before the game starts, $\mathcal{C}^0_2 = \{3, 4, 5, 6, 7, 12\}$ and $\mathcal{C}^0_1 = \{8, 9, 10, 11, 13, 14, 15\}$. Player 12 belongs to $\mathcal{C}^0_2$ since he might receive an offer from both projects. Obviously, he is within reach of project 2 and joins it at $t = 4$ in case its quality is high. However, if

project 2's quality is low and project 1's high, project leader 1 recruits player 12 at $T = 5$.

At $t = 1$, player 3 moves first and waits while, by $A1$ and SR, players 5, 7 and 15 join project 2 and player 8 project 1. Let $team_\gamma^t$ denote the contributors of project $\gamma \in \mathcal{P}$ at the end of period t. Then, $team_1^1 = \{1, 8\}$ and $team_2^1 = \{2, 5, 7, 15\}$. At the end of period 2, $team_1^2 = \{1, 8, 9\}$ and $team_2^2 = \{2, 4, 5, 7, 14, 15\}$. From period 3 on, the teams depend on $k \in K$. How they evolve is depicted in Table 1. At $T = 5$, the teams are identical to those formed at $t = 4$, except of project 1 which includes player 12 if, and only if, k_1^H k_2^L.

	k_1^H k_2^H	k_1^H k_2^L	k_1^L k_2^H	k_1^L k_2^L
$team_1^3$	$\{1, 8, 9, 10\}$	$\{1, 3, 8, 9, 10\}$	same as	same as
$team_2^3$	$\{2, 3, 4, 5, 7, 13, 14, 15\}$	$\{2, 4, 5, 7, 13, 14, 15\}$	k_1^H k_2^H	k_1^H k_2^L
$team_1^4$	$\{1, 8, 9, 10, 11\}$	$\{1, 3, 6, 8, 9, 10, 11\}$	same as	same as
$team_2^4$	$\{2, 3, 4, 5, 6, 7, 12, 13, 14, 15\}$	$\{2, 4, 5, 7, 13, 14, 15\}$	k_1^H k_2^H	k_1^H k_2^L

Table 1: How the teams evolve in Case 1 of Example 6

Players 3 and 6 are most central. Players 4, 5 and 7 join a low quality project 2 in case $k_1^H k_2^L$, while 3 and 6 join high quality project 1 with one more contributor. Otherwise, their payoffs coincide. All other players always join the same team, except of player 12 who, however, remains unrecruited in case k_1^L k_2^L.

It is left to show that players 4 and 5 do not deviate. Suppose first that player 5 waits for an offer from project 1 (instead of joining project 2). Then, player 3 updates his belief about project 2's quality to 0 and joins project 1 at $t = 3$. The teams at this point in time are $team_1^3 = \{1, 3, 8, 9, 10\}$ and $team_2^3 = \{2, 7, 13, 14, 15\}$. At $t = 4$, project leader 1 asks players 6 and 11 if project 1's quality is low and additionally player 4 (just in case he is still available) if it is high. All players accept his offer. Project leader 2 recruits player 12 who updates his belief about its quality to 1 (since he anticipates to be on the SE path). At $T = 5$, player 5 receives project leader 2's offer for sure and project leader 1's if, and only if, its quality is high. Hence, he joins project 1 if offered and otherwise project 2.

Player 5's deviation is profitable if his expected payoff in this case is larger than or equal to the one in the SE. (By $A2$, he aspires to join project 1 if the two payoffs are equal and deviates from the SE.) Player 5's payoff in both cases is depicted in Table 2.

His expected payoff in the SE is $\dot{p}\pi_5^2(10, k_2^H) + (1 - \dot{p})\pi_5^2(7, k_2^L)$. If he deviates it is $\dot{p}\pi_5^1(9, k_1^H) + (1 - \dot{p})(\dot{p}\pi_5^2(7, k_2^H) + (1 - \dot{p})\pi_5^2(7, k_2^L))$. The first term is larger than the second if $\pi_5^2(10, k_2^H) - \pi_5^1(9, k_1^H) > (1 - \dot{p})(\pi_5^2(7, k_2^H) - \pi_5^2(7, k_2^L))$ and player 5 does not deviate.

Player 5's payoff	in the SE	after deviating
$k_1^H\ k_2^H$	$\pi_5^2(10, k_2^H)$	$\pi_5^1(9, k_1^H)$
$k_1^H\ k_2^L$	$\pi_5^2(7, k_2^L)$	$\pi_5^1(9, k_1^H)$
$k_1^L\ k_2^H$	$\pi_5^2(10, k_2^H)$	$\pi_5^2(7, k_2^H)$
$k_1^L\ k_2^L$	$\pi_5^2(7, k_2^L)$	$\pi_5^2(7, k_2^L)$

Table 2: Player 5's Payoff

Suppose that player 5 does not deviate, but that player 4 waits for an offer from project leader 1 (instead of joining project 2). Player 3 again updates his belief about project 2's quality to 0 and joins project 1 at $t = 3$. Then, $team_1^3 = \{1, 3, 8, 9, 10\}$ and $team_2^3 = \{2, 5, 7, 13, 14, 15\}$. At $t = 4$, project leader 1 recruits players 6 and 11 for sure, and player 4 if, and only if, project 1's quality is high. Project leader 2 recruits player 12 who updates his belief about its quality to 1 (since he anticipates to be on the SE path). At $T = 5$, player 4 receives project leader 2's offer if its quality is high and accepts it if he did not yet join project 1. Otherwise he remains unrecruited.

His expected payoff in the SE is $\dot{p}\pi_4^2(10, k_2^H) + (1 - \dot{p})\pi_4^2(7, k_2^L)$. If he deviates it is $\dot{p}\pi_4^1(8, k_1^H) + (1 - \dot{p})\dot{p}\pi_4^2(8, k_2^H)$. The first term is larger than the second if $\dot{p}(\pi_4^2(10, k_2^H) - \pi_4^1(8, k_1^H)) > (1 - \dot{p})(\dot{p}\pi_4^2(8, k_2^H) - \pi_4^2(7, k_2^L))$ and player 4 joins project 2 at $t = 2$. (By $A2$, player 4 aspires to join project 1 if this inequality is weak and deviates from the SE.)

The relation between the inequalities derived for players 4 and 5 depends on $\dot{p}$ and the payoff function. If both of them hold, players 4 and 5 cannot deviate profitably. Otherwise, at least one of them would deviate and a different SE has to be found.

Case 2: If player 5 deviates, player 3 would wait until $t = 4$ and player 6 until $T = 5$ before joining project 1. Both join project 2 before if offered. This induces player 5 to join project 2 at $t = 1$ since project 1's offer never reaches him. The game evolves as initially described in Case 1, though players 3 and 6 join project 1 only at $t = 4$ and $T = 5$, respectively, if project 2's quality is low. This is a SE if, and only if, the inequality derived for player 4 in Case 1 holds. Otherwise, he deviates and waits for project 1's offer.

Case 3: Then, player 3 waits instead until $T = 5$ to join project 1 and player 4 joins project 2 at $t = 2$ since he never receives an offer from project 1. The game evolves as described in Case 1, though players 3 and 6 join project 1 only at $T = 5$, if project 2's quality is low. This is the unique SE if player 4 deviates from the one found in Case 1.

Finally, it is shown that player 3 does not deviate from his SE strategy as long as $p_1 = p_2$. If he waits at $t = 1$, his expected payoff is $p_2\pi_3^2(10, k_2^H) + (1 - p_2)[p_1\pi_3^1(8, k_1^H) + (1 - p_1)\pi_3^1(7, k_1^L)]$ while it is $p_1\pi_3^1(10, k_1^H) + (1 - p_1)\pi_3^1(7, k_1^L)$ if he joins project 1 at $t = 1$. The first term is larger than or equal to the second if

$$p_2\ \pi_3^2(10, k_2^H) + (1-p_2)\ p_1\ \pi_3^1(8, k_1^H) + (1-p_2)\ (1-p_1)\ \pi_3^1(7, k_1^L) \geq$$

$$p_1\ \pi_3^1(10, k_1^H) + (1-p_1)\ \pi_3^1(7, k_1^L).$$

Since $p_1 = p_2 = \dot{p} > 0$, this simplifies to $\dot{p}\ \pi_3^1(8, k_1^H) + (1-\dot{p})\ \pi_3^1(7, k_1^L) \geq \pi_3^1(7, k_1^L)$ and player 3 waits at $t = 1$. Players 3 and 6 are most central in Cases 2 and 3 as well since the teams that emerge are identical to those formed in Case 1.

4.3 Centrality Measure and Related Literature

Conceptually the categorization of players is related with Freeman's (1977) betweeness centrality and Burt's (1992) structural holes. Both select a single most central player who frequently, and as seen in Example 1, differs from the one(s) selected in this model.

A player which fills a structural hole obtains the highest payoff since he brokers information or controls its flow between two groups. He receives an informational rent in an environment in which information is complementary and cross fertilization of ideas benefits both groups. Burt's concept is based on Freeman's betweeness centrality which measures the proportion of paths between two distinct players which contain a third one. For example, in Figure 2, players 3 and 4 have the highest betweeness centrality if the two project leaders are taken as reference since any path between them contains both players. Nevertheless, player 4's expected payoff is not highest. If player 4 were connected to both project leaders, his betweeness centrality would be highest. Then, all players obtain the same expected and realized payoff as shown in the next section.

Whereas betweeness centrality is defined purely with respect to the network, the concept of structural holes requires an interpretation of the network. There are two groups of players which can access each other only via the structural hole player. Each group is seen as a separate entity. Conversely, the centrality measure developed in this paper depends on the TFG, and in particular, on the project leaders' position in the network. It takes into account the agents' strategic considerations, that is, the project leaders' competition to obtain enough contributors and the players' intention to join together a high quality project. Obviously, the set of most central players depends on the players' commitment, the projects' equal payoff division and the unique SE which is selected by $A1$, $A2$ and the players' order of moves.

The agents' strategic behavior might prevent players which are most central according to Freeman or Burt, such as player 4 in Example 2, from taking advantage of their position. The different outcomes of the three centrality measures appear throughout all examples in the previous subsection. According to Freeman's betweeness centrality, players 7 and 8 are most central in Figure 4 of Example 3 while players 6 to 9 are most central using the categorization. In Figure 5 of Example 3, both measures select players 21 and 22 as most central. In Figure 6, all players have the same betweeness centrality while player 4 is most central according to the categorization. In Figure 7, players 3 and 8 have the highest betweeness centrality while players 3 and 4 are most central using the concept derived in this paper. In Figure 8, players 3 to 5 and 8 to 15 have the same betweeness centrality and player 4 might arguably fill a structural hole. In the TFG of Example 6, however, players 3 and 6 are most central.

4.4 Welfare Implications

In a SE inefficient unemployment may arise. Due to the network structure a project leader who did not yet reach the optimal number of contributors may not be able to access more players while there are unrecruited players which would like to join a project.

This occurs, for example, if only one project leader can access category 2 (for different realizations of $k \in K$), such as in Example 5 with $6 > |b^*_\gamma(L)| > 3$, or in a star whose hub is the only barrier player while two of the spokes are project leaders. In Figure 3, something similar may happen if various players are added to the tree that originates in project leader 2. Then, inefficient unemployment obtains in the SE, if project leader 1 needs more than two contributors and project leader 2 leaves some players in the tree unrecruited. Although these are stylized examples, in reality, frequently something similar occurs as is implied by the empirically results in Brüderl and Preisendörfer (1998) and Blumberg and Pfann (2001).

A remedy to fix this inefficiency in the model is to link a project leader with unrecruited players. However, links may be costly and the theoretical analysis of a network formation game that precedes the team formation game would yield useful insights. In reality, the network structure is usually not commonly known. Nevertheless, it might not be difficult and costly to provide platforms for existing and potential entrepreneurs to from additional links, such as fares where local banks, customers, suppliers and representatives of the local administration offer their advice and availability to from links.

From a social point of view it is desirable to include more players in a project than its leader aspires to do. In a SE, even this number may not be reached. Moreover, the players frequently coordinate on one project and one group of barrier players waits until the very end of the game in order to induce the other to join its project (immediately) and thereby to reveal its quality. This is inefficient if once one team is filled the other may pick up the remaining players, but its barrier players prevent it from accessing available players. This inefficiency is inherent in the SE since both groups of barrier players would like to know the more distant project's quality before taking a decision.

In general, more dense networks, that is, networks in which there are more links and a lower diameter, fare better in terms of welfare, as defined by the sum of all agents' payoffs, since players are more easily accessible and more players can be reached on time. However, the project leaders' position matters and a newly created link may allow one of them to "steal" players from the other which might decrease welfare. An additional link may increase welfare as shown in "Changes in the Network Structure" in section 5.

In case more project leaders are added to the network, any player's expected payoff is nondecreasing. Although, the competition for players becomes more severe and this harms project leaders. In reality, there are few examples, such as Silicon Valley, in which such a process is self-reinforcing. Many skilled individuals are competed for by many projects but this attracts more skilled individuals and entrepreneurs. Projects may go bust and release players again. As a consequence, the network is dynamic and its structure changes frequently. In most other places all over the world, the network is not as dynamic and competition between entrepreneurs is different such as shown in Brüderl and Preisendörfer (1998). The model developed in this paper applies to these situations in which the network is roughly stable over a long period of time.

5 Discussion

In this section, various assumptions and extensions of this model are discussed.

The Categorization in more General Cases. The players' categorization extends to more than two quality levels per project and to more than two projects. More categories and intersections between them exist and a player's belief updating is more complicated, though the qualitative nature of the result does not change. If there are more than two projects, for any number of quality levels, the number of categories is equal to the number of projects since some players initially might expect to join each project with a positive probability. Players drop to lower categories over time or join a project and all players which expect to receive a certain number of offers might do so from different projects. Hence, for each category there is a subcategory with different project combinations. In general, a unique SE can be selected if similar assumptions as $A1$ and $A2$ hold.

Changes in the Network Structure. If links are added or destroyed in network η, the categorization of players may change and a different SE may arise. Such changes can be easily dealt with using the framework defined above.

In order to illustrate this, consider Example 2 with $T = 3$ and $p_1 = p_2$, but suppose that in the network depicted in Figure 2 player 4 is connected to both project leaders. In this case, all players are barrier players but only player 4 is one of both projects. In the unique SE, at $t = 1$, players 5 and 6 join project 2 since its leader asks them independently of its quality. If project 2's quality is high, player 4 joins it as well at $t = 1$ and player 3 at $t = 2$. If its quality is low, players 3 and 4 join project 1 at $T = 3$ since both update their beliefs about project 2's quality to 0. All players obtain the same expected and realized payoff. If players 3 and 4 joined project 1 before $T = 3$, players 5 and 6 would wait whether they are offered to join project 1 at $T = 3$. This indicates them its high quality. Otherwise, the two players could still join project 2. Though this deviation does not increase their payoff, by $A2$, they prefer to join project 1 and would deviate.

Informational Assumptions. It is possible to relax the informational requirements for project leaders. Initially, each may be restricted to know his direct neighbors. After recruiting one of them, he gets to know the recruited neighbor's neighbor(s) and so on. In this way the project leader's behavior implied by $A1$ arises endogenously in a SE.

The players' information about the network could be restricted as well. If the players are also categorized when each project's quality is low, then a player only needs to know in which category he is depending on the realized project qualities. To know his exact position in the network is not necessary. In reality, it is therefore not (always) necessary to be linked with the most focal agent(s), such as a project leader or barrier player.

If all agents observe all offers and replies and not only those involving them, then the players update their beliefs about a project's quality earlier, and the game is trivial.

Finally, suppose that each agent is equally likely to be selected as a project leader. First, one is drawn from the set of agents and removed, and then the other among the remaining agents (in order to avoid that one agent obtains two projects). The ensuing game could be solved analogously. However, each player would take into account the probability with which each other agent is a project leader and form corresponding beliefs which enter his expected payoff function. The coordination feature would be lost unless T is quite large and a player does not lose the option to join one project by waiting for a second offer. A project leader's optimal strategy would be unchanged.

Commitment. If a player need not commit, he accepts the first offer he receives but then reneges on his promise if he gets a better offer. Since all players prefer to join the same project, once the two projects have recruited neighbors in category 2, one group of players would renege on its promises.

In Example 2, for $T = 3$, player 3 joins project 1 and players 5 and 6 project 2 at $t = 1$. If offered, player 4 joins project 2 at $t = 2$ since this reveals him project 2's high quality. Player 3 then joins it at $T = 3$. If player 4 does not receive an offer from project 2 at $t = 2$ (since its quality is low), he joins project 1 instead. If, and only if, project 1's quality is high, players 5 and 6 renege on their initial promise to project leader 2 and join project 1 at $T = 3$. All players obtain the same payoff. Either all of them join the same high quality project or two low quality projects each with three agents form.

Each project leader would then recruit players out of reach for the other since they stay with him. Players in category 2 are only recruited if no others are accessible. If a project leader thereby reveals his project's high quality, his chance to keep them increases.

If project leaders need not commit either, they would initially pretend to have a high quality project. At T, they would discard players if the project's quality is low. Hence, the players only get to know a project's quality once they cannot react to it any more.

In reality, project leaders and players frequently commit. Usually, contracts are signed for a certain period and can only be cancelled at early enough prior notice. If one party breaks a contract, fines may be imposed on it. Moreover, in many industries after leaving a company, important employees are prevented from changing to a competitor, supplier or customer during a prolonged period of time.

6 Final Remarks

This paper studies team formation in a network taking into account social ties of economic agents. Two projects compete for players which have imperfect information about their quality. A unique pure strategy SE always exists under weak conditions. The players are categorized depending on their position in the network relative to the two projects and according to whether they may receive two, one or no offers. The categorization is related with a player's SE strategy and his expected and realized payoff. It yields a new centrality measure, which is unrelated to existent concepts in the network literature. Usually, a group of players is most central.

The model's solution implies that economic agents only need to locate in the right category, but that their exact position does not matter, unless they strive to become barrier players. In general, welfare defined as the sum of all agents' payoffs is not larger in any other network than the complete one. Unemployment may prevail in a SE, although project leaders still want to recruit. In a SE, the players are willing to delay their decision to join a closer project in order to solicit information about the more distant's quality.

This behavior is individually rational, though it may be socially inefficient if it prevents a team from reaching its optimal size.

This model can be extended in several ways. The players' skill level may be heterogenous. A project leader may have to recruit several low skilled players just to access a high skilled one. The agents may choose an effort level, which is a continuous variable, or each can allocate an amount of time or money to various projects. Bargaining among project participants could take place or a project leader could post a wage. Moreover, a market for the teams' products might exist. The team which produces earlier captures a higher market share, while the other is more successful if its product's quality is higher and it offers a larger quantity. Though this depends on whether the products are substitutes or complements. Finally, a network formation game that precedes the TFG can be analyzed.

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