Final Report
K-101224
Game Theory: The many faces of equilibrium and allocation

We have investigated various topics in game theory. The motivation for these basically theoretical investigations came either from the theory itself (modelling incomplete information situations, studying old (stable sets, Shapley value) and new (soft correlated equilibrium) solution concepts), or from exploring the applicability of the theory (to oligopoly markets, cost allocation, network bargaining, auctions). Both the strategic and the cooperative approaches are represented among the addressed research questions which range from the very fundamental to the quite applied. During the five years of the project we have also addressed new questions originally not foreseen or planned.

In the proposal we stated that "our goal is to produce a total of 8-12 articles in top quality periodicals of the field, and to have a total of 14-18 presentations at respected conferences". We have succeeded to surpass all these figures: already 15 articles have appeared in well-respected international journals with Impact Factor (and 2-4 more such articles are expected to come out in the near future from the pool of submitted working papers); 8 more articles are published (or being accepted) in various other periodicals; 6 papers have appeared in edited volumes; and during the years we have delivered more than 30 presentations at international conferences and workshops, and more than 10 talks at domestic conferences.

The Corvinus Game Theory Seminar has continued to provide a regular forum (with at least 10 talks each semester) for colleagues and students interested in Game Theory and its applications to Economics and other social sciences. The participants have benefitted from the talks given by an increased number of visiting international speakers. To disseminate information we maintain the webpage http://gametheory.uni-corvinus.hu/index.html .

Following the structure of the project proposal, we summarize the achieved results topic by topic. We list the papers related to this project separately from the general references.

1. Soft correlated equilibrium

Correlated equilibrium is a powerful concept introduced by the Nobel-laureate Robert Aumann (1974). It allows an umpire to improve social welfare attainable in a game by designing a protocol so that the desired outcome is realized in equilibrium without direct enforcement. While Nash equilibrium is a model of „anarchy" being at one end of the spectrum, social welfare maximizing dictatorship lies at the other end. Different forms of correlated equilibria are somewhere in between. Soft correlated equilibrium (SCE) was introduced by Forgó (2010), as a generalization of Aumann's correlated equilibrium. The main purpose of this subproject was to demonstrate that SCE can improve on social welfare in certain important classes of games as compared to other kinds of correlation protocols.

Simple congestion games are models of situations where players can choose and use a service facility and the utility obtained depends only on the number of players using a particular facility. Congestions are penalized by low utility. Forgó (2014a, 2014b) demonstrates that higher social welfare can be achieved by SCE than in the classical correlated equilibria of Aumann (1974), and in the the weak correlated equilibria of Moulin and Vial (1978). The performance is measured by the mediation value and the enforcement value as defined by Ashlagi et al. (2008). Lower and upper bounds for the n-player case and exact values for 2,3 and 4-player games are determined for 2-facility, simple linear congestion games.

Forgó (2015b) shows that simple congestion games are in close relation with prisoners' dilemma games and other social dilemma type games. Thereby, techniques successfully used in congestion games to measure the effectiveness of different kinds of correlation in increasing social welfare can be applied for social dilemma type games. In particular, the mediation value and the enforcement value can be determined or estimated for some special prisoners' dilemma type games. Forgó shows that the mediation value of the soft correlated equilibrium for the linear n-person prisoners' dilemma game is infinite. The enforcement value of soft correlation is 2. The same result is obtained for separable n-person games.

2. Axiomatization of the Nash equilibrium correspondence

In Forgó (2013) some new approaches are suggested to characterize the Nash equilibrium concept in normal form games. These include derivation of the equilibrium production volumes in a Cournot duopoly by the iterated eliminination of strictly dominated strategies, thereby giving an alternative to the fixed point approach.

Forgó (2015a) gives a new axiomatization of the Nash equilibrium correspondence for n-person games based on independence of irrelevant strategies. It is shown to be an equivalent axiomatization to the reduced-game based axiomatization introduced by Peleg and Tijs (1996). Using a flexible general model, Forgó proves that the Nash equilibrium correspondence is the only solution to satisfy the axioms of non-emptiness, weak one-person rationality, independence of irrelevant strategies and converse independence of irrelevant strategies on the class of subgames of a fixed finite n-person game which admit at least one Nash equilibrium. It is also shown that these axioms are logically independent.

3. Oligopoly games

Oligopoly theory is a prime example for the application of game theory to economics. Investigations have been done in three special topics.

(1) ***Endogenous sequencing of price decisions*** The key feature of price-setting games within the framework of homogenous good Bertrand-Edgeworth oligopolies is that the firms may serve less than the demands they are facing. The main difficulty with these models is that one must consider mixed-strategy equilibria, since for the interesting cases there is no equilibrium in pure strategies. Tasnádi (2010) considered the special triopolistic case, with two identical small firms and two periods for which he found that the large-capacity firm will emerge as the endogenous price leader. For the timing problem Tasnádi (2016) proves the endogenous emergence of Forcheimer's model of dominant firm price leadership. In particular, the firm with the largest capacity becomes the price leader.

(2) ***Mixed oligopolies*** In mixed oligopolies there are also public or at least semi-public firms on the market. The aim of this subproject was to investigate how the presence of a public or semi-public firm changes the timing of price decisions, equilibrium prices and social welfare within the framework of Bertrand-Edgeworth competition.

Balogh and Tasnádi (2013) consider mixed duopolies with advance production. As for the case of production to order, they find that, in contrast to the standard version of the Bertrand-Edgeworth game, equilibrium in pure strategies always exists. In addition, for the solution of the timing game they demonstrate the emergence of simultaneous moves in contrast to the production to order version of the same mixed duopoly game (where the timing of decisions does not matter).

Bakó and Tasnádi (2014) extend Kreps and Scheinkman's (1983) celebrated result to mixed-duopolies with linear demands and constant unit costs. They show that quantity

precommitment and Bertrand competition yield Cournot outcomes not only in the case of private firms but also when a public firm is involved. Bakó and Tasnádi (2017) show that the latter result also holds in the case of concave demand functions and strictly convex cost functions.

Rácz and Tasnádi (2016) consider mixed oligopolies in which a social surplus maximizing firm competes with at least two private firms in a capacity constrained Bertrand-Edgeworth framework. They determine conditions under which pure-strategy equilibrium exists. While in the homogeneous good price-setting game with purely private firms pure-strategy equilibrium may not exist for a wide range of capacities, Rácz and Tasnádi show that its mixed version admits a pure-strategy equilibrium for a much wider range of capacities. In addition, they determine and compare the equilibrium outcome with that of the standard Bertrand-Edgeworth oligopoly with only private firms. These results might be particularly useful in modeling energy markets, especially electricity markets, since the storage of electricity is difficult and expensive, capacity constraints play a natural role, and in many countries state-owned firms are present on these markets.

Tasnádi (2013) replaces the public firm with a partially state-owned firm, and provides necessary and sufficient conditions for the existence of equilibrium in pure strategies, and in case of existence determines the equilibrium in pure strategies. In a conference talk Nagy and Tasnádi focus on the equilibrium in mixed strategies and characterize the support of these equilibria. For the special case of linear demand and constant unit costs they determine an equilibrium in mixed strategies and show that the equilibrium behaves "smoothly" as a function of the governmental share. Based on numeric calculations they conjecture that social welfare is maximized if the governmental share equals zero, implying that in the Bertrand-Edgeworth framework full privatization is socially optimal.

(3) ***Mode of production*** Tasnádi (2012) investigates the problem of choosing the right decision variable for an oligopoly model, and finds that if the firms are free to set both prices and their production volume in a way that the firms are "auctioning" their production stocks on the market and they are offering additional amounts at their quoted prices, then in the interesting cases we observe either the emergence of the Cournot-game or Forchheimer's model of dominant firm price leadership.

Tasnádi et al. (2012) give a resolution to the Bertrand-paradox based on evolutionary motivated endogenous preferences.

4. Strategic games with incomplete information

Pintér (2012) gives an overview of the results on the Harsányi Program (Harsányi 1967-68), discusses Harsányi's main intuitions, and presents the formalizations of these intuitions. He sheds light on the deep conceptual problems of modeling incomplete information situations (topological vs. purely measurable type spaces), and concludes that the purely measurable approach seems to be the appropriate framework for the discussed models.

Pintér and Udvari (2012) introduce the concept of generalized type space, and show that the universal generalized type space does exist. Generalized type spaces consist of ordinary types and types such that the players ignore some events, thus, generalized types can model a much broader class of types than ordinary types can. Pintér and Udvari also point out how the notion of common prior can be extended to generalized type spaces, and argue that the common prior can be seen as a coordination device.

Pintér (2014a) shows that the so called universal belief-knowledge space (Meier, 2008) is not complete, that is, there are probability distributions on this space which are not subjective

beliefs (types). Pintér (2014b) points out that if we correct the "logical inconsistency" of the ordinary type spaces then we get a new epistemic model. This new knowledge-belief space has very nice properties: the universal type space does exist, every hierarchy of beliefs is a type, and the universal knowledge structure is complete. In the proposed model, however, in contrast to the famous result by Aumann (1976), the players can agree to disagree, and the epistemic conditions given by Aumann and Brandenburger (1995) are neither necessary, nor sufficient for the players to play Nash equilibrium. On the other hand, the new model can explain the paradoxical ratings by the three big credit rating companies.

5. Cooperative games in general

Pintér (2015) presents a new proof for the Shapley value axiomatization by Young (1985). The result indicates the validity of this axiomatization on classes of games where its validity was not known before.

In a conference presentation Pintér shows that the countable additive core of an infinite TU game is not empty if and only if the game is countably balanced.

Pintér (2016) presents a cardinal convex NTU game with an empty core. The example demonstrates that the notion of cardinal convexity is not an appropriate extension of the TU convexity concept, because in the TU setting convexity implies a well-structured, large, nonempty core.

Németh and Pintér (2017) consider the non-emptiness of the weak sequential core of a TUU game (TU game with uncertainty) as introduced by Habis and Herings (2011) and give a necessary and sufficient condition for its non-emptiness. They also introduce a quite large class of TUU games having a non-empty core independently of the configuration of the utility functions.

Solymosi (2015) proves that for permutation games the kernel is contained in the least core. This result strengthens an earlier result on the inclusion of the kernel in the core in permutation games (Solymosi et al., 2003). By means of a 5-player permutation game (having a non-convex kernel) Solymosi demonstrates that, in a sense, this inclusion result can not be strengthened.

Solymosi and Sziklai (2016) consider the computation of the nucleolus in general TU games. Using the concept of dual game, they show that dually essential and, if the game is monotonic, dually saturated coalitions determine both the core and the nucleolus whenever the core is non-empty. They also show that if the grand coalition is vital then the intersection of essential and dually essential coalitions itself forms a characterization set.

Solymosi (2016) considers the per-capita nucleolus from a computability perspective. He shows that if the core of the game is not empty, coalitions which are not anti-essential in the dual game can be ignored in the computation of the per-capita nucleolus. In specific well-known classes of balanced games (standard tree games, assignment games) this implies a polynomial time computability of the per-capita (and certain other weighted versions of the) nucleolus.

Sziklai, Fleiner and Solymosi (2016) consider the cost allocation game defined on directed acyclic graph (DAG) networks. They discuss the relation of DAG-games with other network-based cost games and demonstrate that in general a DAG-game is not concave, even its core might be empty. An efficiently verifiable condition satisfied by a large class of directed acyclic graphs is shown to be sufficient for balancedness of the associated DAG-game. A network canonization process is introduced and various structural results for the core of

canonized DAG-games are proved. A subset of the coalitions that is sufficient to determine the core is identified.

6. Assignment games

Pintér and van den Brink (2015) show that the traditional TU game type axiomatizations of the Shapley value do not work on the class of assignment games, however, a graph based axiomatization (a' la Myerson) works. They also give a new result on Young's (1985) axiomatization of the Shapley-value that provides new insight into this type of characterization of the Shapley-value.

In a series of conference talks Bednay characterizes all von Neumann-Morgenstern stable sets in an assignment game. With this characterizaton it is easy to prove related results by Shapley (1959), Solymosi and Raghavan (2001), Nunez and Rafels (2013), and some other nice properties of stable sets. Bednay also introduces local stability, a modification of the standard von Neumann-Morgenstern stability concept, and proves that in assignment games every stable set is locally stable, and under some conditions all locally stable sets are also von Neumann-Morgenstern stable.

Nunez and Solymosi (2014) investigate various lexicographic allocation procedures with the property that if the outcome of the procedure is in the core, it is an extreme point of the core. They study procedures based on core lower bounds as well as analogous procedures based on core upper bounds, and derive relations among these and the marginal allocation procedure in balanced TU games. Nunez and Solymosi apply these general results to assignment games. Their main result is that all extreme points of the core in an assignment game can be obtained by a lexicographic optimization procedure run on the dual game. Moreover, this procedure can be easily performed, because, as they show, the dual of an assignment game is completely determined by the dual values of the single-player and of the mixed-pair coalitions, and these dual values can be efficiently computed from the underlying assignment matrix.

In a series of conference talks Bednay observes that the core of a (2+2+2)-sided assignment game has similar structural features to the core of a standard (2+2)-sided assignment game. He shows that the characterization of core stability by Solymosi and Raghavan (2001) in the classical case also holds for (2+2+2)-sided assignment games. By counter examples he demonstrates that this is no longer true even for immediate generalizations, like the (3+3+3)-sided or the (2+2+2+2)-sided assignment games.

7. Applications of cooperative games

Szabó et al. (2012) apply cooperative game theory to medical research. They demonstrate how the Shapley value can also be a useful methodological tool in the integrative analysis of neuroblastoma and pheochromocytoma genomics data.

Dobos and Pintér (2013) apply cooperative game theory to management science. They apply the Shapley value to allocate the profit of cooperation in supply chains.

Pintér and Radványi (2013) consider shortest path games, and give an axiomatization of the Shapley value on this class of optimization games.

Csóka and Pintér (2016) apply cooperative game theory tools to analyze risk allocation situations. They show that no risk allocation method meets three basic fairness properties at the same time: stability -- no group of players has an incentive to deviate, incentive compatibility -- cheating is not profitable, and universal domain -- the rule can be applied for any risk allocation situation.

Balogh, Bátyi, Csóka and Pintér (2012) discuss network models and stability concepts based on the seminal work of Jackson and Watts (2002), and take steps towards the application of network theory to financial networks.

Balogh, Bátyi, Csóka and Pintér (2017) give a detailed discussion and comparison of risk allocation methods. The paper clarifies and unifies the terminologies used in the literature, correct previous mistakes in the literature, and provides examples, counter examples, analytic results and simulations on the considered wide class of risk allocation methods.

8. Other works

In 2012 Forgó, Pintér, and Solymosi served as members of the program and organizing committees of the SING8 Conference held at Corvinus University of Budapest. Forgó and Pintér also served as guest editors of the SING8 conference special issue of Central European Journal of Operations Research. http://link.springer.com/article/10.1007/s10100-015-0421-8

In 2013 Tasnádi successfully defended his thesis „Pure and mixed oligopolies" and was awarded the title „Doctor of the MTA". http://real-d.mtak.hu/519/

In 2014 Solymosi received the degree of Doctor Habilitatus at Corvinus University of Budapest. As part of this procedure he prepared a dissertation entitled „On Set-valued Solutions of Cooperative Games".

In 2015 Forgó successfully defended his thesis „Equilibria in Game Theory: Existence and Generalizations" and was awarded the title „Doctor of the MTA". http://real-d.mtak.hu/728/

In 2015 Pintér received the degree of Doctor Habilitatus at Corvinus University of Budapest. As part of this procedure he prepared a dissertation entitled „On the axiomatizations of the Shapley value".

In a memorial paper marking the 100th birthday of professor Béla Krekó, Forgó and Komlósi (2015) give an account of how Béla Krekó initiated and led a reform process to introduce operations research in the curriculum of the University of Economics, Budapest.

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