A MECHANISM FOR META-BARGAINING PROBLEMS*

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A MECHANISM FOR META-BARGAINING PROBLEMS

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A B S T R A C T

Consider a two-person bargaining problem, where both agents have a particular notion of what would be a just solution outcome. In case their opinions differ, a procedure which leads to a compromise between the two different views is needed. In this paper we propose a mechanism to solve this kind of conflict. Furthermore, we characterize it axiomatically.

Keywords: Mechanism; Meta-Bargaining Problems.

1.- INTRODUCTION

A two-person bargaining situation appears when two individuals are faced with several possible contractual agreements which are beneficial to both of them, but their interests are not entirely identical. How these people decide on a specific result when faced with this kind of situation has been extensively studied in different ways.

A fundamental contribution was furnished by Nash in 1950 who introduced an idealized representation of bargaining situations and provided the axiomatic methodology in order to solve them. According to this approach a solution is sustained by a set of properties which can be interpreted as the ethical criteria of an impartial arbitrator whose role is to recommend a compromise. Since then, several solution concepts have appeared in the literature (see, for instance, Thomson (1995) for a survey).

At present, the multiplicity of reasonable criteria from a normative point of view leads to a dilemma. If the agents agree on one of them, this should be applied. But what happens if the agents' criteria are different? Could this fact be considered in the model of bargaining?. The following situation, analyzed in some experiments by Roth and Murnighan (1982), shows how in real bargaining the agents support different criteria.

Two subjects are given one hundred lottery tickets to divide between them. Each subject's chance of winning a prize is proportional to the number of lottery tickets he receives in the bargaining, but the *money values of prizes is different for the two players: \$20 for the first one and \$5 for the second.*

The experimental results show that there are two focal proposals: split the expected prize equally (20 and 80 tickets respectively, egalitarian solution) and split the lottery tickets equally (50 and 50 tickets, Nash or Kalai-Smorodinsky solutions). The final outcome occupies a spectrum between these two solutions. In Roth and Murnighan's words, *"the observed results suggest that theories which depend only on the feasible set and on the status-quo are insufficiently powerful to capture the complexity of this kind of bargaining"*.

Van Damme (1986) introduced a model, which he called meta-bargaining problem, which considers that the agents support different solution concepts and he proposed a mechanism to solve this kind of situation. He defended it from a strategic point of view.

The aim of this paper is to propose an alternative mechanism for meta-bargaining problems. However, contrary to the van Damme approach, we are interested in the normative approach, that is, we look for a mechanism being the only one satisfying some "desirable" properties.

The paper is organized as follows: in Section 2 the formal model is presented and in Section 3 the *Unanimous-Concession* mechanism is introduced. Section 4 is devoted to the axiomatic study of this mechanism. Some final comments close the paper. The notation used throughout the paper is relegated to an appendix.

2.- PRELIMINARIES

Following Nash (1950), a *two-person bargaining problem* is a pair (S,d), where S is a subset of $\mathbb{R}^2$ and d is a point in S. The points in S represent the feasible utility levels that the individuals can reach if they agree. If this is not the case, then they end up at the disagreement point d.

We will denote by Σ^2 the class of two-person bargaining problems (S,d) such that:

1. S is convex, closed and bounded from above
2. S is comprehensive, that is if $x \in S$ and $x \geqq y$, then $y \in S$
3. There exists $x \in S$ such that $x > d$

A *solution* for bargaining problems is a single-valued function $f: \Sigma^2 \longrightarrow \mathbb{R}^2$ such that for all $(S,d) \in \Sigma^2$, $f(S,d) \in S$, and $f(S,d) \geqq d$.

Note that this is not the usual definition of the solution, since we are asking for single-valued and individually rational ($f(S,d) \geqq d$) solution concepts.

Definition 1.- A *two-person meta-bargaining problem* is a triple [(S,d);f,g] where $(S,d) \in \Sigma^2$ and $f,g: \Sigma^2 \longrightarrow \mathbb{R}^2$ are two solutions for bargaining problems supported by the agents, such that they belong to a specified family $\mathcal{F}$ of possible solutions.

We will denote by $\Sigma^2_{\mathcal{F}}$ the class of two-person meta-bargaining problems.

Definition 2.- A *mechanism* for meta-bargaining problems is a single valued function M: $\Sigma^2_{\mathcal{F}} \longrightarrow \mathbb{R}^2$ such that for any $[(S,d);f,g] \in \Sigma^2_{\mathcal{F}}$, $M[(S,d);f,g] \in S$ and $M[(S,d);f,g;] \geqq d$.

Remark 1.- If $d \in \partial(S)$, then $(S,d) \notin \Sigma^2$ and $[(S,d);f,g] \notin \Sigma^2_{\mathcal{F}}$. In this case we will use the notation $M[(S,d);f,g] = \textit{sup} \{ x \in S \mid x \geqq d \}$.

Remark 2.- Given a mechanism for meta-bargaining problems for fixed solutions $\bar{f}$ and $\bar{g}$, $M[(.,.);\bar{f},\bar{g}]$ is a solution concept for bargaining problems.

Remark 3.- In order to define a mechanism for meta-bargaining problems, it is important to choose the appropriate domain of criteria that can be supported by the agents for two reasons: on the one hand, it should contain the solutions which, in general, can be considered fair for bargaining problems; and, on the other hand, it is needed to ensure the existence of the mechanism. For instance, the domain of solutions of van Damme's mechanism consists on the family of solutions satisfying Pareto optimality, scale invariance, symmetry and risk sensitivity. Moreover he assumes that each agent's proposal gives more utility to himself than his opponent's does.

3.- THE UNANIMOUS-CONCESSION MECHANISM

Definition 3.- In the class of two-person meta-bargaining problems $\Sigma^2_{\mathcal{F}}$ *the Unanimous-Concession mechanism*, U: $\Sigma^2_{\mathcal{F}} \longrightarrow \mathbb{R}^2$, is defined as follows: let $[(S,d);f,g] \in \Sigma^2_{\mathcal{F}}$, then $U[(S,d);f,g] = \lim_{k\to\infty} v^k$ where the sequence v^k is constructed in the following way:

$$v^1 = d$$

and for $k \in \mathbb{N}$, $k > 1$

$$v^k = \inf \{f(S,v^{k-1}),g(S,v^{k-1})\} \qquad \text{if } v^{k-1} \in \text{int}(S)$$

$$v^k = v^{k-1} \qquad \text{if } v^{k-1} \in \partial(S)$$

The interpretation of this mechanism is as follows: each agent has his own proposal, given by the solution functions f and g; thus, for a bargaining problem (S,d), the solution outcome is the result of a step-by-step bargaining process from the disagreement point: at the first step, each agent concedes to the other, an amount according to a unanimous criterion, namely, the maximum amount on which both agents agree. So these *concessions* appear in a "natural" way (v^2 denotes this point). Then, in the next step, each agent applies his solution concept to find the outcome solution of the new bargaining problem (S,v^2) and repeats the process until they both converge in a common solution (see Figure 1). Note that we do not propose a step-by-step process, but only supply a rational psychological model that supports the proposed solution U[(S,d);f,g], which is the limit of the process.

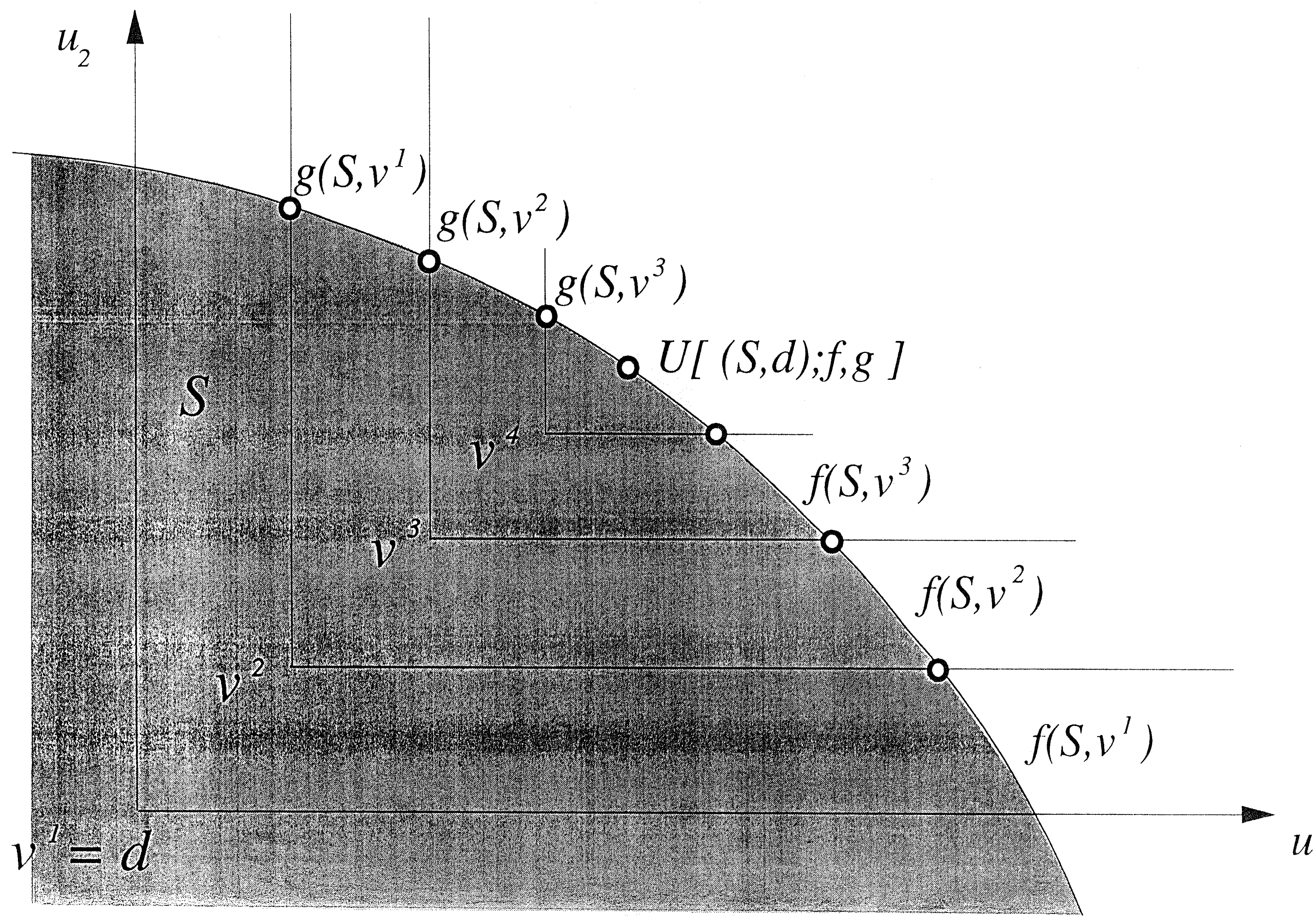

FIGURE 1

The next result proves that this process converges to a point in the feasible set S in every domain $\mathcal{F}$.

Theorem 1.- U is a mechanism for two-person meta-bargaining problems.

Proof:

Being f, g $\in \mathcal{F}$, then $v^k \geqq v^{k-1}$ and the sequence is increasing and bounded. Since S is closed, it converges to a unique point $v^* \in S$, which is greater than or equal to d by construction.■

Depending on the solution functions f and g supported by the agents, the outcome proposed by the *Unanimous-Concession* mechanism could be the disagreement point (for instance, if each agent is dictatorial in his proposal), or an interior or boundary one. This fact will be discussed in the next Section, where we analyze the properties of the proposed solution.

Anbarci and Yi (1992) presented a mechanism with a similar idea: to improve the disagreement point by considering the point at which both proposals coincide (they called it Minimal Agreement Procedure). In order to define the mechanism, they construct two sequences representing the solution outcomes of the two agents in the boundary of S. The proposed result is the limit of both sequences when they exist and coincide. They showed the convergence of such a procedure for a determined set of solutions proposed by the agents, but they did not analyze it from a strategic nor axiomatic point of view.

If we compare our mechanism with the Minimal Agreement Procedure, the idea is essentially the same. But some remarks are needed in order to point out some shortcomings within Anbarci and Yi's work. On the one hand, the proof of the existence result is incorrect as Example 1 shows. On the other hand, Anbarci and Yi restrict the family of acceptable solutions to the ones which satisfy midpoint domination and that in all steps the proposal made by each agent gives more to himself than his opponent gives him, that is,

$$f_1(S,v^k) \geqq g_1(S,v^k) \text{ and } g_2(S,v^k) \geqq f_2(S,v^k) \text{ for all } k.$$

The former assumption, in spite of appearing to be an innocuous condition, is very strong: it does not allow players, for instance, to support Nash and Kalai-Smorodinsky solutions, since the order in which these solutions appear could change from one step to another (this fact is shown in Example 2).

EXAMPLE 1

Let $S \equiv$ ComCo $\{(0,3),(2,3),(3,0)\}$ and let $d = (0,0)$. If $f(S,d) = (2,3)$ and $g(S,d) = (1.5,3)$, thus $d^2 = (1.5,3)$ and the procedure defined by Anbarci and Yi cannot continue.

EXAMPLE 2

Let $S \equiv$ ComCo $\{(0,3),(2.5,2.25),(3.2),(3,0)\}$ and let $d = (0,0)$. Thus if f is the Nash solution and g is the Kalai-Smorodinsky one, in the first stage $f_1(S,d^1) > g_1(S,d^1)$, but in the second one the converse inequality holds.

The aforementioned deficiencies are solved in our approach and the *Unanimous-Concession* mechanism exists in a wider class of admissible solution concepts supported by the agents. Anyway, in the family where the Minimal Agreement mechanism is well defined, it coincides with the *Unanimous-Concession* mechanism.

4.- PROPERTIES: AXIOMATIC CHARACTERIZATION

The formulation of a solution in the Axiomatic Theory of Bargaining consists of formalizing a group of "desirable" properties that a solution should satisfy as axioms, and establishing the existence of a unique alternative for each conflict verifying all of them. We will consider two kinds of axioms for meta-bargaining problems. As we have commented, for fixed $\bar{f}$ and $\bar{g}$, $M[(.,.);\bar{f},\bar{g}]$ is a classical bargaining solution and, as such, it could verify the usual axioms in this context. On the other hand, for a fixed $(\bar{S},\bar{d})$, $M[(\bar{S},\bar{d});.,.]$ depends on the solution supported by the agents, and some new properties can be defined in order to analyze the behavior of the mechanism when the agents' proposals change.

The following classical bargaining axioms, which will be used in the remainder of the paper, are standard in the literature, its interpretations can be found in Thomson (1995).

A solution $f: \Sigma^2 \longrightarrow \mathbb{R}^2$ is said to be:

(WPO) *Weak Pareto optimal* if for all $(S,d) \in \Sigma^2$, $f(S,d) \in WPO(S)$.

(PO) *Pareto optimal* if for all $(S,d) \in \Sigma^2$, $f(S,d) \in PO(S)$.

(SIR) *Strong individually rational* if for all $(S,d) \in \Sigma^2$, $f(S,d) > d$

(d-CONT) *Continuous with respect to the disagreement point* if for any sequence $\{d^n\}$ which converges onto d, if the problems (S,d), $(S,d^n) \in \Sigma^2$ for all n, then the sequence $\{f(S,d^n)\}$ converges onto $f(S,d)$.

It is quite straightforward to extend these conditions to mechanisms for meta-bargaining problems as follows:

A meta-bargaining mechanism, M: $\Sigma_{\mathcal{F}}^2 \longrightarrow \mathbb{R}^2$, is said to be *weak Pareto optimal* (**WPO**) [*Pareto optimal* (**PO**)] if for any f,g $\in \mathcal{F}$, M[(.,.);f,g] is WPO [resp. PO]. It is said to be *strong individually rational* (**SIR**) if for any f,g $\in \mathcal{F}$, M[(.,.);f,g] is SIR. It said to be *continuous with respect to the disagreement point* (**d-CONT**) if for any f,g $\in \mathcal{F}$, M[(.,.);f,g] is d-CONT.

Now, we introduce some new properties that have sense in the context of meta-bargaining problems.

(**IM**) *Impartiality*: For all $[(S,d);f,g] \in \Sigma_{\mathcal{F}}^2$, $M[(S,d);f,g] = M[(S,d);g,f]$.

Impartiality says that all the opinions within the class of admissible ones $\mathcal{F}$, should have the same value, regardless of whose opinion it is. We think this is a "natural" condition to demand from the mechanism when the solutions proposed by agents represent their ethical principles.

This is a property that van Damme or Anbarci and Yi's mechanisms do not verify, since they assume that the proposal of each agent gives more to himself that his opponent's does. So, if a problem [(S,d);f,g] can be considered in their domain, the situation [(S,d);g,f] cannot. Consequently, the agents are not treated equally: the set of possible fair criteria, in fact, is different for both of them. The bankruptcy problems, which can be analyzed through a cooperative bargaining approach (see Dagan and Volij (1993)) are a clear illustration of this. The agents will propose a solution (proportional with respect to the claims, equal-loss from the claims,...) which will only depend on justice criteria and not on the claims of a particular problem. Then, from a normative point of view, it does not make sense to demand that each agent's proposal provides more utility for himself than his opponent's does.

(UN) *Unanimity.* If $f(S,d) = g(S,d)$, then $M[(S,d);f,g] = f(S,d)$.

Unanimity says that when the agents agree on which the appropriate criterion is, this should be applied.

When we allow the agents to propose solutions which are not efficient, this property is not, in general, compatible with *weak Pareto optimality* of the mechanism. In order to obtain the compatibility of both conditions, we introduce the following axiom.

(ImDP) *Improvement of dominated proposals.*

For all $[(S,d);f,g] \in \Sigma^2_{\mathcal{F}}$, if $f(S,d) \leqq g(S,d)$ then

$$M[(S,d);f,g] = M[(S,f(S,d));f,g]$$

And analogously, if $g(S,d) \leqq f(S,d)$ then

$$M[(S,d);f,g] = M[(S,g(S,d));f,g]$$

Improvement of dominated proposals says that if one of the proposals is below the other one, the result of the problem with the lower proposal as a disagreement point coincides with the result of the initial problem. When f and g are Pareto optimal solutions, this property coincides with *unanimity*. Moreover, it implies that the outcome of the mechanism is above the dominated proposal.

(MAP) *Monotonicity with respect to the agent's proposal.*

For all $f,f',g \in \mathcal{F}$ such that $g_1 \leqq f'_1 \leqq f_1$ and $f'_2 = f_2 \leqq g_2$,

$M_1[(S,d);f',g] \leqq M_1[(S,d);f,g]$ for all $(S,d) \in \Sigma^2$.

And analogously, for all $f,g',g \in \mathcal{F}$ such that $g_1 \leqq g'_1 \leqq f_1$ and $f_2 = g'_2 \leqq g_2$,

$M_2[(S,d);f,g] \geqq M_2[(S,d);f,g']$ for all $(S,d) \in \Sigma^2$.

Monotonicity with respect to the agent's proposal means that if the solutions supported by one agent does not change and the proposal of the other agent only changes by increasing the possible payoff for himself, then the mechanism should not decrease the outcome assigned to this agent with respect to the initial result.

We are interested in defining the unique mechanism which verifies **SIR, PO, IM, ImDP** and **MAP**. It is easy to observe that the *Unanimous-Concession* mechanism, in general, does not verify *weak Pareto optimality* although f and g do. If we ask for a mechanism to satisfy *weak Pareto optimality*, we must restrict the class of acceptable solutions for the agents. From now on, we consider the class

$$\mathcal{F}_1 = \{ f \in \mathcal{F} \mid f \text{ is (d-CONT) and (SIR) } \}$$

Theorem 2.- In the class of meta-bargaining problems $\Sigma^2_{\mathcal{F}_1}$ the *Unanimous-Concession* mechanism verifies **WPO**, **SIR** and **d-CONT**.

Proof:

By construction, if f and g are SIR, so is the *Unanimous-Concession* mechanism. Now if we suppose that **WPO** does not hold for the *Unanimous-Concession* mechanism, let $[(S,d);f,g] \in \Sigma^2_{\mathcal{F}_1}$ such that

$$U[(S,d);f,g] = v^* = (v_1^*,v_2^*) \in int(S)$$

where

$$v_1^* = \lim_k \min (f_1(S,v^k),g_1(S,v^k))$$

$$v_2^* = \lim_k \min (f_2(S,v^k),g_2(S,v^k))$$

thus there is a subsequence such that (without loss of generality)

$$v_1^* = \lim_k f_1(S,v^k)$$

Consider the sequence $\{v^k\}$. Thus it converges to v^* and by applying d-CONT to f, $v_1^* = f_1(S,v^*)$ which contradicts the fact that $f(S,d^*)$ is SIR.

In order to prove that the *Unanimous-Concession* mechanism verifies **d-CONT**, let f,g be two fixed solutions in $\mathcal{F}_1$, and let $(S,d^n) \in \Sigma^2$ a sequence of problems such that $\{d^n\}$ converges onto $d \in int(S)$. As the function *inf* is continuous, and f,g are d-CONT, the sequence *inf* $\{f(S,d^n),g(S,d^n)\}$ converges onto *inf* $\{f(S,d),g(S,d)\}$, that is $\{(v^n)^2\}$ converges onto v^2. By applying the same argument to the problems $(S,(v^n)^2)$, we obtain that $\{(v^n)^3\}$ converges onto v^3, and successively, $\{(v^n)^*\}$ converges onto v^*.■

Remark 4.- Note that in the class $\mathcal{F}_1$ the *Unanimous-Concession* mechanism satisfies **WPO** even if the agents' proposals do not verify WPO. In order to obtain this property, other possible classes could be used, such as the ones used by van Damme or by Anbarci and Yi. Also note that whenever f and g are in the class $\mathcal{F}_1$ so is the bargaining solution U[(.,.);f,g].

In order to obtain a *Pareto optimal* (**PO**) mechanism in the same class $\mathcal{F}_1$, we are going to modify the *Unanimous-Concession* mechanism following the standard method of constructing its lexicographic extension.

Definition 4.- In the class of two-person meta-bargaining problems $\Sigma^2_{\mathcal{F}_1}$ the *Extended Unanimous-Concession* mechanism, $U^*: \Sigma^2_{\mathcal{F}_1} \longrightarrow \mathbb{R}^2$, is defined as the lexicographical extension of U[(S,d);f,g], for any [(S,d);f,g] in $\Sigma^2_{\mathcal{F}_1}$.

In $\mathbb{R}^2$ this extension, being U[(S,d);f,g)] weak Pareto, can be expressed as $U^*[(S,d);f,g] = sup \{ x \in S \mid x \geqq U[(S,d);f,g] \}$.

Theorem 3.- The *Extended Unanimous-Concession* mechanism U* is the only mechanism in the class of meta-bargaining problems $\Sigma^2_{\mathcal{F}_1}$ verifying **IM**, **ImDP**, **MAP**, **SIR** and **PO**.

Proof:

We have already seen that U is **SIR** in the class of meta-bargaining problems $\Sigma^2_{\mathcal{F}_1}$ and by construction so is U*. Also, by definition, U* is **PO**. On the other hand, it is easy to prove that U* verifies **IM**, **ImDP**, and **MAP** given the properties of the *inf* function, and the way of constructing the solution.

In order to prove the uniqueness, let G be any meta-bargaining mechanism with the aforementioned properties. Now given $[(S,d);f,g] \in \Sigma^2_{\mathcal{F}_1}$ define

$$f^*(S,d) = \begin{cases} f(S,d) & \text{if } f_1(S,d) > g_1(S,d) \\ g(S,d) & \text{if } g_1(S,d) > f_1(S,d) \end{cases}$$

$$g^*(S,d) = \begin{cases} g(S,d) & \text{if} \quad f^*(S,d) = f(S,d) \\ f(S,d) & \text{if} \quad f^*(S,d) = g(S,d) \end{cases}$$

By applying **IM**,

$$G[(S,d);f,g] = G[(S,d);f^*,g^*]$$

since in any problem (S,d) the proposals given by (f,g) are the same as the one given by (f*,g*). First we consider the case in which none of the following inequalities are fulfilled: $f(S,d) \leqq g(S,d)$ or $g(S,d) \leqq f(S,d)$. In this case if we consider

$$f'(S,d) = \mathit{inf}\ (f^*(S,d),g^*(S,d))$$

it is verified that

$$f^*_1(S,d) > f'_1(S,d) = g^*_1(S,d)$$
$$f^*_2(S,d) = f'_2(S,d) < g^*_2(S,d)$$

and applying **MAP** to the problems [(S,d);f*,g*] [(S,d);f',g*]

$$G_1[(S,d);f,g] = G_1[(S,d);f^*,g^*] > G_1[(S,d);f',g]$$

and applying **ImPD** to the problem [(S,d);f',g]

$$G_1[(S,d);f',g] = G_1[(S,f'(S,d));f',g]$$

Once again it is possible to apply **ImDP**, but now to the problem [(S,f'(S,d));f',g] and by repeating successively this process, and from the definition of U[(S,d);f,g],

$$G_1[(S,d);f',g]= U_1[(S,d);f',g]$$

which in turn, as a result of the properties of the *Unanimous-Concession* mechanism, is equal to

$$U_1[(S,d);f^*,g^*] = U_1[(S,d);f,g],$$

that is,

$$G_1[(S,d);f,g] > U_1[(S,d);f,g]$$

With an analogous argument, by taking g'(S,d) = *inf* (f*(S,d),g*(S,d)), we will obtain that

$$G_2[(S,d);f,g] > U_2[(S,d);f,g]$$

but verifying the solutions G and U* **PO**, and U* being the lexicographical extension of U, then both coincide. In the remaining cases we can suppose, without loss of generality, that f(S,d) $\leqq$ g(S,d) and then the condition **ImDP** implies that

$$G[(S,d);f,g] = G[(S,f(S,d));f,g] \text{ and}$$
$$U[(S,d);f,g] = U[(S,f(S,d));f,g]$$

In this new problem we repeat the above argument and, if in all cases there always exists a proposal which is greater than the other, this process will converge, by strong individual rationality and Pareto optimality, to the proposal made by the *Extended Unanimous-Concession* mechanism.■

It is worth noticing the independence of the axioms characterizing the *Extended Unanimous-Concession* mechanism (theorem 4). The following examples establish them.

(i) The *Unanimous-Concession* mechanism satisfies all the axioms except **PO**.

(ii) The mechanism which provides for any $[(S,d);f,g] \in \Sigma^2_{\mathcal{F}}$ the Nash solution for bargaining problems, fails to be **ImPD** but satisfies the rest of the axioms.

(iii) The mechanism which assigns the lexicographic extension of the Dictatorial criterion of agent i for all $[(S,d);f,g] \in \Sigma^2_{\mathcal{F}}$ verifies **PO**, **IM**, **ImPD** and **MAP** but does not satisfy **SIR**.

(iv) The following mechanism verifies all the axioms except **MAP**.

$$M[(S,d);f,g] = \begin{cases} M[(S,f(S,d));f,g] & \text{if } f(S,d) \leqq g(S,d) \\ M[(S,g(S,d));f,g] & \text{if } g(S,d) \leqq f(S,d) \\ \text{Nash solution of } (S,d) & \text{otherwise} \end{cases}$$

(v) **IM** fails to be satisfied by the mechanism defined as follows,

$$M[(S,d);f,g] = \begin{cases} f(S,d) & \text{if } f(S,d) \in PO(S) \text{ and } g(S,d) \leqq f(S,d) \text{ does not hold} \\ U^*[(S,d);f,g] & \text{otherwise} \end{cases}$$

but this mechanism verifies **PO**, **SIR**, **ImPD** and **MAP**.

FINAL COMMENTS

In this paper we defend the *Unanimous-Concession* mechanism for meta-bargaining problems from a normative point of view. We introduce some properties, which we consider to be reasonable, about the behavior of mechanisms which try to conciliate different distribution principles and show that the *Unanimous-Concession* mechanism is the only one satisfying all of them.

It is worth noticing the differences between this work and the other two commented throughout the paper: van Damme's mechanism is based on the renouncement of payoffs greater than those demanded by and for oneself, whereas the idea behind the *Unanimous-Concession* mechanism is that each agent ensures for himself the worst of the different utility levels proposed for him. On the other hand, the class of admissible solutions where our mechanism exists is wider than those allowed by van Damme or Anbarci and Yi. Finally, in this paper we adopt the axiomatic approach to analyze the conflicts at hand, the main interest of van Damme's work being the strategic study of these problems.

A P P E N D I X

Vector notation: for $x,y \in \mathbb{R}^2$, $S \subseteq \mathbb{R}^2$

$x \geqq y$ means $x_i \geq y_i$ for all $i = 1,2$

$x > y$ means $x \geqq y$ and $x \neq y$

$x > y$ means $x_i > y_i$ for all $i = 1,2$

inf $\{x,y\} = (\min \{x_1,y_1\}, \min \{x_2,y_2\})$

sup $\{x,y\} = (\max \{x_1,y_1\}, \max \{x_2,y_2\})$

WPO(S) is the set of weak Pareto optimal points of S

$$WPO(S) \equiv \{ x \in S \mid \forall x' \in \mathbb{R}^2,\ x' > x \Rightarrow x' \notin S \}$$

PO(S) is the set of Pareto optimal points of S

$$PO(S) \equiv \{ x \in S \mid \forall x' \in \mathbb{R}^2,\ x' > x \Rightarrow x' \notin S \}$$

Topological notation: for $S \subseteq \mathbb{R}^2$

int(S) stands by the interior of set S

$\partial(S)$ stands by the boundary of S

Convexity notation: for $A \subseteq \mathbb{R}^2$

Co(A) will denote the convex hull of A

ComCo(A) will denote the comprehensive and convex hull of A

$$ComCo(A) = \{ x \in \mathbb{R}^2 \mid x \leqq z \text{ for some } z \in Co(A) \}$$

R E F E R E N C E S

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