Levine

TO: Political Economy Luncheon Group
FROM: Ronald Rogowski
DATE: February 25, 1999

The reading for TUESDAY, March 2, 1998, NOON at the FACULTY CENTER is:

Alternative Collective-Goods Models of Military Alliances: Theory and Empirics

by

John A.C. Conbeare

and

James C. Murdoch

and

Todd Sandler

If you do **not** receive invitations and/or papers but would like to, please call **Nancy Gusten** at: **310-825-2163** or e-mail at: **ngusten@polisci.ucla.edu.**
Paper suggestions are welcome.

BEST ARTICLE AWARD

The Best Article Award for 1993 was again a tie. "Monetary Rewards and Decision Costs in Experimental Economics" by Vernon L. Smith and James M. Walker was chosen along with "Imperfect Competition and Basing Point Pricing" by Thomas Gilligan. The two papers were chosen from approximately 50 published and 330 submitted during that period. The selection committee of Walter Oi, chair, University of Rochester, J. Allan Hynes, University of Toronto, and Mark Bils, University of Rochester, felt that both were significant articles that point out additional directions for future research.

When subjects behave in a fashion that is contrary to wealth maximization, economists frown, psychologists smile, and sociologists write. It encourages some to argue that money matters little. In "Monetary Rewards and Decision Costs in Experimental Economics," Smith and Walker contend that when the relative monetary rewards for rational behavior are small, subjects may not put forth the effort to make rational decisions. Based on a survey of 31 experimental studies, they show that (1) increased rewards shift the central tendency of the data toward the predictions of rational models, and (2) higher rewards reduce the variance of the data around the predicted outcome. They advance an implicit model in which each subject maximizes the net reward of participation, which equals the expected monetary reward less the subject's implicit decision costs. Optimality is attained by balancing the benefits of higher rewards against the effort cost of reducing "error."

The practice of establishing a mill price at a basing point and a price schedule as a function of distance from that base point irrespective of the seller's location attracted considerable attention in the late 1940s. Stigler offered a "second best" argument for basing point pricing, namely that it facilitated policing a cartel agreement when demands are stochastic. Given a stable-delivered price schedule, Haddock (1982) argued that firms at the edges of the market (away from the base point) confront a kinked demand curve, which confers upon them a degree of market power. Firms at the basing point can be competitive; and given their relative size in relation to the spatially differentiated market, they establish a price umbrella which is exploited by the firms on the periphery. In "Imperfect Competition and Basing Point Pricing," Gilligan carefully examines the conditions that could support a stable basing price structure, and the assumptions necessary to arrive at Haddock's results. When the product is homogeneous, Bertrand competition must prevail among base site firms. Cooperation among peripheral firms is sufficient but not necessary to support a stable delivered price structure. Gilligan develops a model that can integrate the views of both Stigler and Haddock.

ALTERNATIVE COLLECTIVE-GOODS MODELS OF MILITARY ALLIANCES: THEORY AND EMPIRICS

JOHN A.C. CONYBEARE, JAMES C. MURDOCH, and TODD SANDLER*

How should the defense activities of allies be aggregated to determine the alliance-wide level of defense? Two alternative models—best shot and weakest link—are contrasted with simple summation of defense spending or manpower for aggregating allies' defense efforts. We extend the joint product model to include these methods of aggregation, and devise an empirical procedure to test between best-shot and weakest -link models. We apply this test to four alliances: Triple Alliance (1880–1914), Triple Entente (1880–1914), Warsaw Pact (1963–1987), and NATO (1961–1987). The testing procedure can be applied to other collective choice situations.

I. INTRODUCTION

In a seminal article, Mancur Olson and Richard Zeckhauser [1966] characterized the North Atlantic Treaty Organization (NATO) in the mid-1960s as a group of allies who shared a *pure* public good in the form of deterrence. To qualify as a pure public good, a good's benefits must be nonexcludable (i.e., available to all group members once provided) and nonrival in consumption (i.e., consumption opportunities associated with a unit of the good do not decline with the number of users). Pure public goods are characterized by free-riding behavior owing to nonexcludability, which permits individuals to partake in the benefits of the good without expending their own scarce resources. Olson and Zeckhauser also demonstrated that a pure public good, such as deterrence, is associated with an exploitation hypothesis, whereby the large agents (allies) shoulder the payment burdens of the small agents (allies). Using data from 1964, Olson and Zeckhauser [1966, 274–77] established that defense burdens are positively correlated with the economic size of the allies as measured by gross national product (GNP).

Over the next twenty-five years, a large literature has generalized and extended the Olson and Zeckhauser collective-goods theory of alliances. Van Ypersele de Strihou [1967] recognized that defense expenditures could generate country-specific private benefits (e.g., disaster relief, protection of colonies, management of domestic unrest) along with purely public deterrence. With the presence of ally-specific benefits, the strength of the exploitation hypothesis is attenuated since a small ally might willingly shoulder a relatively large burden, provided that this ally views its defense expenditures as possessing a large share of nation-specific benefits. In a series of articles, Murdoch, Sandler and others[1] formulated a joint product model in which the military activity of an ally yields pure public, impure public, and/or private

* The authors are, respectively, Professor of Political Science, University of Iowa, Associate Professor of Economics, University of Texas-Dallas, and Professor of Economics, Iowa State University. The authors wish to thank two anonymous referees for helpful comments. This paper's research was funded by the National Science Foundation, grant SBR-922253. Sole responsibility for any shortcomings and the views expressed rests with the authors.

1. Also see Conybeare and Sandler [1990], Cornes and Sandler [1986], Dudley and Montmarquette [1981], McGuire [1990], Oneal and Elrod [1989], and Sandler [1977].

Economic Inquiry
Vol. XXXII, October 1994, 525–542

jointly produced outputs or benefits. If the benefits, derived from the allies' military expenditures, were from a single purely public good, then the joint product model would obviously degenerate to the model of Olson and Zeckhauser [1966]. Murdoch and Sandler [1984], Sandler and Forbes [1980], and Sandler and Murdoch [1990] have shown that the joint product model outperforms the pure public good (deterrence) model for NATO during various time periods.

In recent years, a number of important contributions to the collective-good analysis of alliances have appeared. These include the inclusion of foreign trade considerations (Wong [1991]), marginal cost-differentials among allies (McGuire [1990], Weber and Wiesmeth [1991]), leader-follower behavior (Bruce [1990]), and median-voter considerations (Dudley and Montmarquette [1981], Murdoch, Sandler, and Hansen [1991], and Okamura [1991]). McGuire and Groth [1985] engineered an econometric procedure for distinguishing between allocative processes (e.g., noncooperative and cooperative) within an alliance, while subsequent work by Sandler and Murdoch [1990] operationalized this econometric procedure.

Until now, collective-good models of alliances have computed alliancewide defense levels by simply summing the allies' expenditures. However, the appropriate manner for aggregating defense efforts among allies may depend on geographical, strategic, and technological determinants. For example, the defense efforts of the weakest ally (or link) along a front may determine the strength of the allies' defenses, since the enemy's ability to penetrate behind the front hinges on the weakest fortification (Hirshleifer [1983]). In consequence, the minimal defense level of the allies, and not the sum, determines alliance capabilities.

The purpose of this paper is fivefold. First, we intend to look at different methods of aggregating allies' military expenditures to determine alliancewide defense levels. Three procedures—summation, weakest link, and best shot—are examined.[2] Second, the joint product model is extended to permit methods of aggregation other than summation. Third, a number of alliances are studied empirically based upon the reduced-form equations corresponding to joint products and weakest-link, or best-shot models. Fourth, we devise an empirical procedure to test between the weakest-link and best-shot models of alliances. Fifth, we employ this nested test procedure on four alliances to investigate whether our alternative aggregation functions are more appropriate than summation. Our findings suggest that the Triple Alliance (1880–1914) is best described by the best-shot model, the Triple Entente (1880–1914) by weakest link, and NATO (1961–1987) and the Warsaw Pact (1963–1987) by neither. For the latter two alliances, summation may be the most appropriate way of calculating the aggregate defense level, but further work is needed. The tests presented are by no means definitive, since only three aggregation functions are considered and other qualifications are not included. Thus, our results must be viewed as an initial attempt to explore empirically nonsummation social composition functions.

Our analysis is of general interest, inasmuch as it suggests a procedure for distinguishing which functions for aggregating public good contributions best fit a particular alliance. Furthermore, the procedure is also applicable to collective good problems (e.g. pollution control, infrastructure provision) other than military alliances.

2. Hirshleifer [1983] was the first to use the terminology of weakest link and best shot. Alternative forms of public supply aggregation are discussed in Cornes and Sandler [1986, ch. 7], Cornes [1993], Vicary [1990], Harrison and Hirshleifer [1989] and Van Huyck, Battalio, and Beil [1990]. The Harrison and Hirshleifer [1989] paper distinguishes between different aggregation technologies in an experimental framework, while the Van Huyck et al. [1990] paper uncovered coordination failures in an experimental setting. This latter coordination game followed the weakest-link model.

II. TECHNOLOGIES OF PUBLIC SUPPLY AGGREGATION

The technology of public supply indicates the manner in which the agents' provision of the public good is combined to yield the public good level for the group. Let q^i denote the ith ally's provision of defense, and Q represent the group's provision of defense. The standard technology employed in the study of alliances is that of summation:

$$Q = \sum_{i=1}^{n} q^i, \tag{1}$$

in which n is the number of allies. Summation implies perfect substitutability between the q^is so that the identity of the provider is immaterial; a unit of defense for any ally has the same impact on alliancewide defense.

An alternative technology is that of weakest link in which

$$Q = \min\,(q^1,\ldots,q^n), \tag{2}$$

so that the smallest contribution by any member of the group determines the collective provision of the good. The weakest-link model may apply to the scenario in which a military alliance fortifies a front against a common threat. If alliancewide security depends on keeping the enemy from breaking through, then the poorest fortification along the perimeter determines alliancewide defense capabilities. For a defensive alliance relying on conventional armaments to forestall an aggressor's advance, a weakest-link representation might be more appropriate than summation. France and Russia in the Triple Entente found themselves in this position vis-à-vis the threat of aggression from the Triple Alliance prior to World War I. The least-fortified sectors of the front were apt to draw the attack and, thus, determine the security level for the entire alliance. The weakest-link technology may be appropriate for a wide range of public good scenarios. Prophylactic actions to forestall the advance of a disease, a plague, or a pest abide by the weakest-link technology. Hirshleifer [1983] offered the apt example of dike building around a circular island; the lowest portion of the dike determines the residents' ability to withstand a flood. Beautification programs for neighborhoods or cities may also correspond to the weakest-link model, since the least-attractive yard or residence may become the standard for judging the entire neighborhood. Maintaining a secret (or intelligence) from an enemy also represents a weakest-link technology.

In contrast, a best-shot technology equates aggregate provision levels of the collective good to the largest individual effort:

$$Q = \max\,(q^1,\ldots,q^n). \tag{3}$$

For alliances, the best-shot representation might apply to a security arrangement in which some allies have the technological capability to annihilate an enemy in a preemptive attack. For this scenario, the ally with the most formidable strike force might serve to measure alliancewide defense strength. Prior to the Cuban missile crisis, the United States had a first-strike advantage over the Soviet Union; consequently, the defense level of NATO may well have depended on the U.S. military expenditure until shortly after 1963. After the crisis, the Soviet Union augmented its nuclear arsenal so that it would never again be in such a weak bargaining position. A best-shot technology might be germane to a "Star-Wars" defense in which one or more allies possesses sufficient defensive weapons to neutralize an attacking nation's nuclear missiles shortly after launch. Best-shot technologies might also apply to an offensive alliance, such as the Triple Alliance, that initiates an attack, since the ally whose arsenal is most capable of inflicting the heaviest initial losses on the enemy may well determine the outcome of the war. Other best-shot examples include the discovery of a cure (or treatment) for a disease, the achievement of a research breakthrough, slaying a dragon (Bliss and Nalebuff [1984]), or the gathering of intelligence.

Although this paper focuses on only three methods of public supply aggregation, many other kinds exist. A constant elasticity of substitution (CES) technology,

$$Q = [\sum_{i=1}^{n} (q^i)^v]^{1/v}, \tag{4}$$

is capable of including summation ($v = 1$), best-shot ($v \to \infty$), weakest-link ($v \to -\infty$), and other aggregation technologies depending on the value of the exponential parameter, v (Cornes [1993]). Another technology applies weights to the sum of the q^is. If an alliance contains two different defense systems, then the technology of weakest link might be more suited to one set of weapons (e.g., conventional forces) and best shot to the other set (e.g., strategic nuclear). Yet another technology is *critical mass*, in which the security derived by the allies is a function of the summed contributions of the allies. Furthermore, this function generates a sigmoid curve so that up to a critical total contribution the margin is increasing and, thereafter, is decreasing. This critical inflection point may depend upon the opposing alliance's level of expenditure. Many possibilities exist. Advanced analyses can devise procedures for testing the applicability of these technologies along the lines of the tests offered in this paper.

III. THEORETICAL MODELS

Pure Public Good Models of Alliances

This subsection presents the pure public good model where the allies derive a single defense output—deterrence—from military expenditures. The presentation focuses on the weakest-link model; the summation and best-shot models are summarized in a table.

For the weakest-link representation, the smallest military expenditures or effort of the allies determine the defense level, Q, for the alliance. The quasi-concave, strictly increasing utility function for the decision-making oligarchy in the ith ally is

$$U^i = U^i(y^i, Q), \tag{5}$$

where U^i is utility for the ith ally and y^i is the ally's consumption of a private numeraire good. By substituting equation (2) into (5), we can write the utility function as

$$U^i = U^i[y^i, \min (q^1, \ldots, q^n)] \tag{6}$$

for each i. Throughout the analysis, the technology of public supply aggregation is substituted for Q, the alliancewide defense effort, in the utility function. Substituting equation (1) into (5) would allow the summation technology to apply, while substituting equation (3) into (5) would allow the best-shot technology to apply.

The resource or budget constraint for the ith ally is

$$I^i = y^i + pq^i \tag{7}$$

in which I^i is national income and p is the per-unit price of the defense activity. The per-unit price of the private numeraire is set equal to one in (7). We have chosen a simple linear trade-off, since our primary focus is on empirical estimation. Our data are not sufficient to account explicitly for more complex constraints. Maximizing utility subject to the resource constraint gives a set of first-order conditions that can be expressed as[3]

$$MRS^i_{Qy} = p, \quad q^i \le q^j, \quad j = 1, \ldots, n, \tag{8}$$

and

$$MRS^j_{Qy} \ge p, \quad \text{for all } j \ne i, \tag{9}$$

in which MRS^i_{Qy} is the ith ally's marginal rate of substitution between defense and the private good, and is equal to $(du^i/dQ)/(dU^i/dy^i)$. These conditions indicate that the weakest-link ally (ally i) equates MRS^i_{Qy} and the per-unit price of defense. Since the weakest-link ally is the first to achieve an equality for q^i between MRS_{Qy} and p, allies whose analogous equalities occur at a higher level of defense spending would satisfy the inequality in equation (9) *evaluated at* the defense effort, q^i, of the weakest link.

From the first-order conditions, we have the following demand function, f^i, for defense

$$q^i = \min [f^1(I^1, p), f^2(I^2, p), \ldots, f^n(I^n, p)], \tag{10}$$

for ally i. This equation indicates that the ith ally's demand for defense depends on its own income and the price of defense when i is the weakest link. If, however, ally i requires a level of defense that exceeds the weakest-link's defense expenditures so as to equate MRS^i_{Qy} and price, then ally i will match the weakest-link's defense levels.[4] With a weakest-link technology, there is no reason to contribute beyond min (q^j), the weakest-link's contribution, since such behavior adds to costs but not to benefits. Equation (10) implies that nonweakest-link allies' defense demand depends on the weakest link's income, I^j, and on the per-unit price of defense. An equilibrium is achieved when equation (10) is satisfied for all i; all allies' defense expenditures are set equal to

$$\min_j [f^j(\cdot)]$$

and, hence, to one another's defense expenditures in equilibrium.

The Pareto-optimal or efficiency condition associated with the weakest-link model requires the sum of the allies' marginal rates of substitution to equal n times the per-unit price of defense (Hirshleifer [1983, 378], Harrison and Hirshleifer [1989, 210]).[5] With weakest link, this follows because *every* ally must provide defense at a level equal or above the lowest contributor's level for any marginal benefit to be derived from q^i. If everyone is identical in taste and endowment, the Nash equilibrium is an efficient solution under a weakest-link technology.

Table I summarizes the key features for the standard summation and best-shot technologies in the case in which defense is a pure public good. The summation case is well-known and requires little discussion (see Cornes and Sandler [1986, ch. 5]). Each ally's demand depends on its own income, the per-unit price of defense, and spillins, $\tilde{Q}$, from the other allies. Spillin is measured by the sum of the other allies' military expenditures. Owing to interactions between an ally's demand for q^i and the defense demand of the other allies, the system of allies' demands in Table I for

3. For an interior solution where ally i is the weakest link, these conditions are

$$y^i\!: U^i_y - \lambda = 0 \qquad q^i\!: U^i_Q - \lambda p = 0,$$

where subscripts on U denote partial derivatives and λ is a Lagrangian multiplier. If q^i is greater than $\min_j \{q^j\}$, then the left-hand side of the second condition is greater than or equal to zero.

4. What is being matched is a crucial consideration and may differ in different alliance scenarios. For a conventional war alliance, arsenal strength per mile of exposed border might be matched. If a time-series analysis is utilized and exposed border is constant over time, then defense levels serve as an adequate proxy for defense levels per mile of exposed border. Since our analysis is time series, we stick with defense levels as the measure of strength. Another possibility involves matching defense per capita. We do not use this alternative variable for the match, because we feel that conventional warfare involves protecting perimeters not citizens per se. Hence, the strength per person does not appear as compelling for a security measure as defense per mile of exposed border. Per-capita defense would be more appropriate if equity, rather than efficiency, were our primary concern. For guerrilla warfare, however, a per-capita measure might be a better proxy for security.

5. The Pareto-optimal condition is found by maximizing the ith ally's utility subject to the constancy of the other allies' utility levels, a linear resource constraint for the alliancewide group, and the requirement that $q^i = \min(q^j)$ for *all* i. The choice variables are the individual defense efforts (q^is) and the private benefits (y^is).

TABLE I
Two Alternative Pure Public Good Models[a]

Summation Technology	
Technology:	$Q = \sum_{i=1}^{n} q^i$
Utility function:	$U^i = U^i(y^i, q^i + \tilde{Q}^i)$ with $\tilde{Q}^i = \sum_{j \neq i} q^j$
Nash condition:	$MRS^i_{Qy} = p$ for every i
Demand functions:	$q^i = q^i(I^i, p, \tilde{Q}^i)$
Pareto condition:	$\sum_{i=1}^{n} MRS^i_{Qy} = p$
Best Shot	
Technology:	$Q = \max_j (q^j) \quad j = 1,\ldots,n$
Utility function:	$U^i = U^i[y^i, \max_j(q^j)]$
Nash condition:	$MRS^i_{Qy}(\hat{q}^i) = p, \ \hat{q}^i > q^j, \quad j = 1,\ldots,n, \quad i \neq j$
Demand functions:	$q^i = f^i(I^i, p) \ \hat{q}^i > q^j, \quad j = 1,\ldots,n, \quad i \neq j$
	$q^j = 0, \ j \neq i$
Aggregate demand:	$Q = \max_j [f^j(I^j, p)]$
Pareto condition:	$\sum_{i=1}^{n} MRS^i_{Qy} = p, \ \hat{q}^i > q^j, \ j = 1,\ldots,n, \ i \neq j$
	$q^j = 0, \ j \neq i$

[a]THREAT can be added as an exogenous factor in the utility and demand functions. The weakest-link model is in the text.

summation is best estimated as a simultaneous equation system (Sandler and Murdoch [1990]). The Nash equilibrium is characterized by underprovision of defense, because allies do not account for the marginal benefits that their defense allocation confers on other allies—i.e.,

$$\sum_{j \neq i} MRS_{Qy}{}^j$$

is ignored in the Nash condition.

The bottom half of Table I displays the best-shot model. In the table, $\hat{q}^i$ denotes the level of defense for ally i who achieves an equality between his marginal rate of substitution and the price of defense at the highest defense level, $\hat{q}^i$. Since marginal benefits drop to zero when the jth ally's defense expenditure is less than or equal to the best shooter's defense expenditure level, there is no gain from contributing unless an ally is the best shooter. Consequently, the best shooter's demand is a function of its income and price, while all other allies' defense levels are zero. Alliancewide aggregate demand is simply the demand of the best shooter, since no one else contributes—an extreme case of free-riding results. As with summation, a comparison of the Nash and Pareto conditions indicates that Nash equilibrium will be characterized by underprovision.

The best-shot equilibrium displayed in Table I assumes that the identity of the best shooter is unambiguous. If, however, two or more allies are nearly equal in military strength, then which will be the best shooter may be probabilistic. That is, a mixed-strategy Nash equilibrium may then characterize the simultaneous-move game, much as is often the case in a Chicken game in which at least one player, but not more than one, needs to act. This important consideration is ignored here, because the four alliances examined below have a clear best shooter.

In reality, it is difficult to find cases where the hypothesized contribution patterns for weakest-link (i.e., matching behavior) or best-shot (i.e., only the best shooter providing defense) models are observed. For best-shot scenarios, most allies maintain some defense forces even if they rely in large part on a dominant ally to underwrite their security.[6] To formulate a model more in line with observations, we must account for ally-specific benefits and alliancewide public benefits derived from defense expenditures. Thus, a joint product framework that accounts for diverse technologies of public supply aggregation must be modeled.

Joint Product Models of Alliances

A more realistic set of demand functions can be generated by combining one of the three aggregation technologies with a joint product model, in which a unit of the defense activity, q, gives rise to multiple outputs. As before, we focus the discussion on the weakest-link technology. We assume that each unit of defense activity q produces two outputs: an ally-specific private output, x^i, and an alliancewide public output, Z.[7] The latter could represent deterrence. As before, a linear trade-off between the private consumption good y and the defense activity exists via the resource constraint. In addition, each unit of the defense activity, q^i, serves as an input in producing two outputs, x^i and z^i, via the joint product relationships. The joint product relationship for the ally-specific output is

(11) $$x^i = r^i(q^i), \quad i = 1,\ldots,n,$$

which is increasing, strictly concave and twice continuously differentiable. The weakest-link technology is applied to the alliancewide output so that

(12) $$Z = \min_j (z^j),$$

where

(13) $$z^j = g(q^j), \quad j = 1,\ldots,n.$$

This latter function is increasing, strictly concave, and twice continuously differentiable. The ith ally's utility function is

(14) $$U^i = U^i(y^i, x^i, Z; T)$$

in which T denotes an exogenous threat variable, such as the military expenditures of the opposing alliance or the change in these expenditures. The exogenous threat variable is now included to anticipate our empirical estimation in section V. By equations (11)–(13), the utility function can be written as

6. When, however, defense is subdivided into components, such as strategic, tactical, and conventional weapons as for NATO, only the best shooter (the U.S.) provided nuclear strategic weapons until the 1960s. Thereafter, only three allies provided nuclear weapons. In terms of strategic weapons, a best-shooter result is, indeed, observed.

7. The model can be easily generalized to allow for more outputs.

$$U^i = U^i\{y^i, r^i(q^i), \min_j [g(q^j)], T\}. \tag{15}$$

The relevant resource constraint is

$$I^i = y^i + pq^i. \tag{16}$$

Maximizing utility in equation (15) subject to (16) yields the following first-order conditions for the weakest-link ally:[8]

$$r^{i\prime} MRS^i_{xy} + g' MRS^i_{Zy} = p, \tag{17}$$

in which $r^{i\prime}$ and g' denote the marginal productivity of the defense activity in producing the private and public defense outputs, respectively. Primes indicate derivatives (e.g., $dr^i/dq^i = r^{i\prime}$), and the subscripts on the marginal rate of substitution denote the outputs being traded off. The left-hand side of (17) depicts the marginal rate of substitution between defense and the private good for the weakest-link ally. Equation (17) indicates that the productivity-weighted sum of the marginal rates of substitution derived from the defense activity, is equated to the per-unit price of defense.

The first-order conditions associated with the constrained maximum can be used to derive the demand function for the defense activity via the implicit function theorem. For the weakest-link model, this demand function is

$$q^i = q^i(I^i, p, T), \tag{18}$$

because the relevant marginal utility expressions only depend on the exogenous threat T, individual private consumption y^i, and defense activity q^i, and the latter two variables are endogenous.

For allies other than the weakest-link, the first-order conditions can be written as

$$r^{j\prime} MRS^j_{xy} + g' MRS^j_{Zy} \geq p, \tag{19}$$

in which the marginal rates of substitution are evaluated, in part, at the defense level for the weakest-link ally that satisfies equation (17). Since only the smallest defense level determines the alliancewide defense benefit, any contribution by the larger defenders above this level must be solely based on country-specific benefits received.[9] With joint products, matching behavior between allies needs not result owing to ally-specific benefits. Nevertheless, nonweakest-link allies will not contribute past the point at which their marginal rate of substitution between defense activity and private benefits equals the per-unit price of defense, and may stop short of equality.

The demand for defense of these nonweakest-link allies is

$$q^j = q^j(I^j, p, q^i, T), \quad j \neq i, \tag{20}$$

which, unlike equation (18), also depends on the weakest-link ally's defense expenditures, q^i. This follows because the marginal utility expressions in the first-order conditions depend on q^i, owing to the weakest-link technology. In comparing equations (18) and (20), we see an easy means for distinguishing between the two kinds of allies in a set of recursive estimating equations. That is, the nonweakest-link allies' defense demands depend on the weakest-link's defense level.

Based on earlier comparative static analysis of joint product models (Murdoch and Sandler [1984, 88–90]), the response of defense demand to income in equations (18) and (20) is positive for normal goods, whereas the response of defense to price is negative. Furthermore, the response of defense to threat is predicted to be positive. In equation (20), the response of

8. If more joint products are derived from the defense activity, then additional weighted *MRS* expressions would be required in equation (17).

9. Since the $g(\cdot)$ function does not differ between allies and is monotonically increasing, we have $z^i \leq z^j \Leftrightarrow q^i \leq q^j$.

TABLE II
Two Alternative Joint Product Models[a]

Summation Technology	
Joint product relations:	$x^i = r^i(q^i),\ z^i = g(q^i),\ \tilde{Z} = h(\tilde{Q})$
Utility function:	$U^i = U^i(y^i, x^i, z^i + \tilde{Z}, T)$
Nash condition:	$r^{i\prime} MRS^i_{xy} + g' MRS^i_{Zy} = p$
Demand functions:	$q^i = q^i(I^i, p, \tilde{Q}, T)$
Pareto condition:	$r^{i\prime} MRS^i_{xy} + \sum_{i=1}^{n} g' MRS^i_{Zy} = p$
Best Shot	
Joint product relations:	$x^i = r^i(q^i),\ Z = \max_j [g(q^j)],\ j = 1,\ldots,n$
Utility function:	$U^i = U^i(y^i, x^i, Z, T)$
Nash condition:	$r^{i\prime} MRS^i_{xy} + g' MRS^i_{Zy} = p$ (best shot)
	$r^{j\prime} MRS^j_{xy} = p,\ j \neq i$ (other allies)
Demand functions:	$q^i = q^i(I^i, p, T)$ (best shot)
	$q^j = q^j(I^j, p, q^i, T),\ j \neq i$ (other allies)
Pareto condition:	$r^{i\prime} MRS^i_{xy} + \sum_{i=1}^{n} g' MRS^i_{Zy} = p$

[a]The weakest-link model is in the text.

defense in ally j to changes in the weakest-link ally's defense, q^i, depends on the consumption relationship between private and public output, x and Z. If these goods are complementary, then a positive response is expected; if, however, these goods are substitutes, a negative response is likely, unless such a response would make ally j the weak link.

In Table II, we list the key features of the joint product model when the summation and best-shot technologies are applied to the alliancewide public output. Since the summation model is discussed in the literature, we need only highlight the demand function,

$$q^i = q^i(I^i, p, \tilde{Q}, T), \quad i = 1,\ldots,n, \tag{21}$$

in which $\tilde{Q}$ is the aggregate defense expenditures in the other allies.

When the best-shot technology is applied to the joint product model, the allies that are not the best shot *still have a positive demand for defense owing to the ally-specific defense output*; hence, their defense expenditure q^j is not zero in contrast to the pure public good model. The best-shot ally chooses q^i to satisfy a Nash condition identical to equation (17), while the other allies equate their weighted marginal rates of substitution between the private defense output and the numeraire to the per-unit price of defense. The best shot's demand is

$$q^i = q^i(I^i, p, T), \tag{22}$$

while the other allies' demand is

$$q^j = q^j(I^j, p, q^i, T), \quad j \neq i \tag{23}$$

which depends, in part, on the defense expenditures of the best shot since alliance-wide defense $Z = \max(z^j)$ is an argument in these allies' marginal utility expressions. Once again, we get a recursive system of demand equations for estimating purposes.

Table II also lists the Pareto-optimal conditions for the alternative models.[10] The signs of the comparative statics terms agree with corresponding terms of the weakest-link model. For example, the sign of the response of defense to $\tilde{Q}$ for summation technology is dependent on the consumption relationship of the joint products, as is the case of the sign of $\partial q^j / \partial q^i$ for allies other than the best shooter in the best-shot model.

IV. EMPIRICAL MODELS

In this section, we consider alternative empirical models for four different alliances—the Triple Entente, the Triple Alliance, the Warsaw Pact, and NATO. The empirical models are motivated by the reduced-form theoretical demand equations given in (18), (20), (22), and (23). Specifically, we test weakest-link and best-shot specifications against an unrestricted model that includes both specifications as restrictions. Since it is possible to reject or fail to reject both the weakest-link and best-shot models for any particular country, the testing procedure gives an indirect way to identify alliances which may be characterized by some other defense technology (e.g., summation, or CES). We do not, however, investigate aggregate models per se. Since additional tests are needed before we can draw definitive conclusions, our findings are merely suggestive.

Equation (20) shows the hypothesized relationship for the non-weakest-link allies' defense activity under a weakest-link technology. A plausible linear statistical model corresponding to this hypothesis is

$$DEF_t = \beta_0 + \beta_1 INC_t + \beta_2 WEAK_t + \beta_3 THREAT_t + \varepsilon_t, \tag{24}$$

where DEF_t denotes annual defense activity for a nonweakest-link ally, INC_t denotes annual income, $WEAK_t$ represents the defense activity of the weakest link ally, $THREAT_t$ measures the annual defense activity of the ally's enemy, the βs are unknown parameters, and ε_t is a random error term. The defense activity level is the dependent variable owing to our theoretical construct (see footnote 4). If, however, we had specified a different decisionmaker (e.g., median voter) or had been concerned with equity, then per-capita measures would have been appropriate (see Murdoch, Sandler, and Hansen [1991]). Relative price figures for *DEF* are unavailable, requiring that we drop the price term from all of the empirical specifications. As shown below, our empirical methodology facilitates a country-by-country testing procedure. Hence, to the extent that the relative prices remain constant within a country, our results should be robust with respect to the price term. In a weakest-link alliance, equation (18) indicates that the weakest-link ally's defense demand can be specified as

$$WEAK_t = \beta_0 + \beta_1 INC_t + \beta_3 THREAT_t + \varepsilon_t, \tag{25}$$

10. The Pareto-optimal condition for the weakest-link model is

$$r^j MRS^j_{xy} + \sum_{i=1}^{n} g^i MRS^i_{Zy} = np$$

where the coefficient on the spillin term in equation (24) is necessarily set to zero (i.e. $WEAK_t$ in (24) has a zero coefficient).

Specifications (24) and (25) define a recursive system of equations and the unknown parameters can be efficiently estimated using ordinary least squares (OLS), assuming independent and identically distributed error terms. With annual data, however, independence of the errors is unlikely, and we hypothesize a first-order autoregressive process for the errors.

Similarly, linear empirical models can be specified for best-shot alliances. Equation (23) shows the hypothesized relationship for a nonbest-shot ally that is a member of a best-shot technology alliance. As a statistical model, this can be written

$$DEF_t = \delta_0 + \delta_1 INC_t + \delta_2 BS_t + \delta_3 THREAT_t + \varepsilon_t, \tag{26}$$

with the new term denoting the defense activity of the best-shot ally. Based on equation (22), the best-shot ally's demand for defense can be written as

$$BS_t = \delta_0 + \delta_1 INC_t + \delta_3 THREAT_t + \varepsilon_t, \tag{27}$$

where the coefficient on the spillin term is again set to zero. Specifications (26) and (27) also define a recursive system of equations for the alliance.

From an econometric point of view, we do not want to specify an alliance as either weakest link or best shot a priori. Rather, we wish to distinguish between the two paradigms empirically. Our approach is to first examine the best-shot and weakest-link nations in each alliance. We estimate two unrestricted models; first,

$$WEAK_t = \zeta_{10} + \zeta_{11} INC_t + \zeta_{12} BS_t + \zeta_{13} THREAT_t + \varepsilon_t, \tag{28}$$

and second,

$$BS_t = \zeta_{20} + \zeta_{21} INC_t + \zeta_{22} WEAK_t + \zeta_{23} THREAT_t + \varepsilon_t. \tag{29}$$

Then, empirical evidence of a weakest-link alliance occurs when $\zeta_{12} = 0$ and $\zeta_{22} \neq 0$. That is, the best-shot ally appears to behave just like any other ally [equation (24)] in terms of its empirical specification. Similarly, evidence of a best-shot alliance is when $\zeta_{22} = 0$ and $\zeta_{12} \neq 0$, making the weakest-link ally appear to behave like the other alliance members [equation (26)]. Within this framework, both the unrestricted and the maintained or restricted model can be estimated thereby facilitating construction of standard likelihood ratio test statistics (see Judge et al. [1988]). Moreover, since we hypothesize first-order autoregressive errors, we use a maximum likelihood estimation procedure developed by Beach and MacKinnon [1978].

The likelihood ratio test statistic is distributed Chi-square with degrees of freedom equal to the number of restrictions, and is computed as minus two times the difference between the unrestricted and restricted log-likelihood function values. It is possible that both ζ_{12} and ζ_{22} equal zero or that neither ζ_{12} nor ζ_{22} equals zero. In such instances, we would not have statistical evidence to distinguish between the best-shot and the weakest-link models.

The other allies in each of the alliances can be tested in a similar fashion. From specifications (24) and (26), we see that an unrestricted model with both the best-shot (BS_t) and weakest-link ($WEAK_t$) variables entered as independent variables can be used to test the alternative restrictions. Therefore, with

$$DEF_t = \zeta_0 + \zeta_1 INC_t + \zeta_2 BS_t + \zeta_3 WEAK_t + \zeta_4 THREAT_t + \varepsilon_t \tag{30}$$

as the unrestricted model, evidence of weakest-link behavior is found when

$\zeta_2 = 0$ and $\zeta_3 \neq 0$. On the other hand, $\zeta_2 \neq 0$ and $\zeta_3 = 0$ provides evidence in favor of best shot. Again, we determine which technology best describes alliance behavior by estimating the unrestricted and restricted models and then comparing likelihood function values.

As with the first set of tests, it is possible that no clear evidence will be found to support either technologies. If ζ_2 and ζ_3 are both not equal to zero, we can examine the coefficient estimates to distinguish between technologies. A summation technology would suggest that both estimates would have similar values, thus implying that the two variables (BS_t and $WEAK_t$) could be added together. Dissimilar values, such as opposite signs, would favor an alternative specification of the spillin term. Less can be inferred if $\zeta_2 = \zeta_3 = 0$. A simple summation over all allies may still not be rejected; however, a complete search over other specifications would be necessary to actually test different hypotheses.

V. EMPIRICAL RESULTS

The variables DEF_t, $WEAK_t$, BS_t, $THREAT_t$, and INC_t take on different definitions depending on the ally and alliance under consideration. A single or comparable data source, covering the range of nations and time periods studied here, simply does not exist. For all allies, we use gross national product (GNP) or gross domestic product (GDP), expressed in U.S. dollars to measure INC_t. The military activity variables, (allies' defense activity, DEF_t, weakest-link's defense effort, $WEAK_t$, best shot's defense effort, BS_t, and the enemy's defense effort $THREAT_t$) are measured with military expenditure data in NATO and the Warsaw Pact nations. Since most of the previous modelling of the NATO alliance was estimated using information from the Stockholm International Peace Research Institute (SIPRI), these same data were also used here. In the case of the Warsaw Pact, data from the U.S. Arms Control and Disarmament Agency's (ACDA) annual reports are used, since they were already converted to constant U.S. dollars, using the appropriate exchange rates. SIPRI data on Eastern Europe is, by its own admission, unreliable.

However, we use military manpower to measure defense activity in the pre-World Waf I allies, owing to the absence of real military expenditures data. Although manpower is a stock rather than a flow, this is unlikely to distort the measure of military activity, since the flow of annual military expenditures would have been highly correlated with the stock of manpower. Manpower was the major source of military strength and the factor intensity of military activity did not experience any major changes during the period. The paucity of data necessitated our estimating pre-World War I national incomes by multiplying Crafts [1983] per capita estimates by population (from Mitchell [1975]) and interpolating to deduce intra-decennial GDP. The definitions of all variables are presented in Table III (by alliance) for easy reference when considering the empirical results. In order to be consistent with the formal model and to avoid ad hoc selection of weak links and best shooters, we define the weakest link (best shooter) as the ally with the lowest (highest) military effort. We recognize that in some cases this may result in the selection of allies that may not fit well with more qualitative judgments of the identity of the weakest link or best shooter. Additionally, the variables used in the regression analysis are expressed in their natural logarithm form. The data are, thus, unit free, and the regression coefficient estimates can be interpreted as elasticities.

For the pre-World War I alliances, the test statistics presented in Table IV suggest that the Triple Alliance can be classified as following best-shot technology behavior. The weakest-link model is rejected for both Italy (the weakest link) and Austria,

TABLE III
Variable Descriptions by Alliance[a]

	Triple Alliance (1880–1914)
DEF_t	Military manpower for Austria[b]
$WEAK_t$	Military manpower for Italy[b]
BS_t	Military manpower for Germany[b]
$THREAT_t$	Total military manpower in France, the United Kingdom, and Russia[b]
INC_t	Real GDP in 1970 U.S. dollars for each ally[c]
	Triple Entente (1880–1914)
DEF_t	Military manpower for France[b]
$WEAK_t$	Military manpower for the United Kingdom[b]
BS_t	Military manpower for Russia[b]
$THREAT_t$	Total military manpower in Austria, Italy, and Germany[b]
INC_t	Real GDP in 1970 U.S. dollars for each ally[c]
	Warsaw Pact (1963–1987)
DEF_t	Real military expenditures in 1988 U.S. dollars for Bulgaria, Czechoslovakia, East Germany, Poland, and Romania[d]
$WEAK_t$	Real military expenditures in 1988 U.S. dollars for Hungary[d]
BS_t	Real military expenditures in 1988 U.S. dollars for the Soviet Union[d]
$THREAT_t$	Total military expenditures in 1988 U.S. dollars for NATO[d]
INC_t	Real GNP in 1988 U.S. dollars for each ally[d]
	NATO (1961–1987)
DEF_t	Real military expenditures in 1980 U.S. dollars for Belgium, Canada, France, W. Germany, Italy, the Netherlands, Norway, and the United Kingdom[e]
$WEAK_t$	Real military expenditures in 1980 U.S. dollars for Denmark[e]
BS_t	Real military expenditures in 1980 U.S. dollars for the U.S.[e]
$THREAT_t$	Real military expenditures in 1980 U.S. dollars for the Soviet Union[f]
INC_t	Real GDP in 1980 U.S. dollars for each ally[e]

[a]All variables expressed in natural logarithms in the statistical models.
[b]Obtained from *Statesman's Yearbook* [1879–1914]. Military manpower is in 100s and excludes reserves.
[c]Obtained from Crafts [1983] and Mitchell [1975].
[d]Obtained from U.S. Arms Control and Disarmament Agency [various years].
[e]Obtained from Stockholm International Peace Research Institute [various years] and International Monetary Fund [various years].
[f]Obtained from Brada and Graves [1988] and U.S. Congress, Joint Economic Committee [1981, 1986–1988].

because the higher Chi-squares (lower p-values) mean more confidence in rejecting the restrictions. The best-shot model is not rejected in Germany (the best shooter) or in Austria when using an alpha level of .10.

The implication of rejecting the weakest-link model in Italy is that the coefficient estimate on BS_t, which equals the military manpower of Germany, the best shooter, is statistically significant in the Italian equation. Rejection of the weakest-link model indicates that BS_t is not dropped from the specification and, hence, the Italian model looks like equation (26).

By similar reasoning, failing to reject the best-shot specification in Germany implies that the coefficient estimate on $WEAK_t$, the military manpower of Italy, the weakest link, is not significant in the demand regression for Germany. In Austria, the BS_t coefficient is significant, while the $WEAK_t$ coefficient is not. Thus, the Austrian specification also takes the form given in equation (26).

In Table IV, the test results for the Triple Entente allies provide partial evidence to support a weakest-link classification. The best-shot model is rejected for Russia (the best shooter), while the weakest-link model cannot be rejected for the weakest-link ally—the United Kingdom. France, however, displays evidence of behavior consistent with both types of technologies, since the coefficient estimates on defense activity by the best shot and weakest link are both significant. Thus, the unrestricted model, equation (30), appears to outperform both of the restricted models in the case of France.

The coefficient estimates for the pre-World War I alliance nations are presented in the top half of Table V, which shows the estimates from the models that are maintained after the testing procedure. A zero entry in the table indicates that the estimate was not significantly different than zero in the unrestricted model. All of the income elasticities for the Triple Alliance and Triple Entente are positive and less than one. They range in value from .185 to .726, illustrating why country-by-country estimation, in contrast to pooled estimation, is better in these types of studies. With the exception of the estimate on BS_t in the French equation, all of the spillin elasticities are positive and less than one. This finding is consistent with the hypothesis of complementarity between the joint products. Evidently, these allies obtained significant private benefits from their military activities.

The results with respect to the pre-World War I alliances are suggestive and intuitively appealing. The aggressor alliance, the Triple Alliance, appears to exhibit best-shot behavior, while the defensive alliance, the Triple Entente, seems to behave like a weakest-link alliance. Germany's status as best shooter in the Triple Alliance is clear; its manpower averaged over 600,000 men at arms, while Italy and Austria each averaged 300,000. Since Austria and Germany were the first countries to declare war (on Serbia, Russia and France, in that order), the model estimations appear consistent with the association of best shot with offensive alliances.

Similarly, the Entente's apparent behavior as a weak-link alliance fits well with its historical position as a defensive block organized as a counter to German hegemony in central Europe. Russia had to respond positively to the military effort of the U.K., the alliance's weak link, since Germany could choose to strike either east or west at the outbreak of war. This meant that Russia could not turn the Entente into a best-shot alliance, because of its geographic isolation from its two allies. Had France and the U.K. chosen to free ride on their best shooter, then Germany could simply turn the brunt of its attack west instead of east. In 1914, Germany invaded France first, driving through its unfortified Belgian border. However, the results do suggest some slight French free riding on Russia, which may be due to the fact that France and Russia had the tightest alliance of any pre-war dyad, binding both to assist the other against Germany. By 1907, France and the U.K. had entered into elaborate "military conversations" designed to elicit matching contributions to a war against Germany.

The results for the Warsaw Pact allies are not very clear-cut. Hungary, the small-

TABLE IV

Chi-square Statistics Based on the Likelihood Ratio Tests of Alternative Model Specifications (p-values in parentheses)

Country	Maintain Weakest-Link Model		Maintain Best-Shot Model	
	Triple Alliance			
Italy[a]	9.33	(.00)	NA	
Germany[b]	NA		2.56	(.11)
Austria	3.01	(.08)	.137	(.71)
	Triple Entente			
United Kingdom[a]	1.02	(.31)	NA	
Russia[b]	NA		2.96	(.09)
France	6.75	(.01)	11.79	(.00)
	Warsaw Pact			
Hungary[a]	1.76	(.18)	NA	
Soviet Union[b]	NA		.88	(.35)
Bulgaria	4.22	(.04)	2.58	(.11)
Czechoslovakia	.00	(.98)	.43	(.51)
E. Germany	4.97	(.03)	4.27	(.04)
Poland	1.00	(.00)	6.24	(.01)
Romania	6.22	(.01)	2.55	(.11)
	NATO			
Denmark[a]	.39	(.53)	NA	
United States[b]	NA		.26	(.61)
Belgium	3.53	(.06)	2.65	(.10)
Canada	2.96	(.09)	2.61	(.10)
France	1.83	(.18)	1.41	(.23)
W. Germany	2.75	(.10)	.514	(.47)
Italy	.18	(.67)	1.43	(.23)
The Netherlands	9.94	(.00)	.53	(.40)
Norway	1.16	(.28)	.026	(.87)
United Kingdom	.482	(.49)	.130	(.72)

[a]Weakest Link
[b]Best Shot
NA—not applicable

est spender, behaves like a weakest-link ally [equation (25)]. In contrast, the Soviet Union results indicate that the best-shot paradigm can not be rejected for this ally. Bulgaria and Romania also display behavior consistent with the best-shot technology. For Czechoslovakia, the spillin terms are not statistically significant. In East Germany and Poland, however, both spillin coefficients are significant. Moreover, the difference between the estimates appear large enough to question whether simple aggregation is appropriate. Probably some linear or non-linear aggregation rule is necessary to best fit these data.

When taken as a group, the Warsaw Pact estimates support the "demand" interpretation of the military expenditures equations. This is consistent with empirical work on NATO by Murdoch and

TABLE V
Maximum Likelihood Estimates for the Maintained Models[a]

Country	*INC*	*BS*	*WEAK*	*THREAT*	*RHO*
		Triple Alliance			
Italy	.215	.682**	NA	-.088	.182
Germany	.584**	NA	0	.051	.539**
Austria	.701**	.239**	0	-.125*	.690**
		Triple Entente			
United Kingdom	.726**	0	NA	-.044	-.931**
Russia	.318**	NA	.363**	-.053	.595**
France	.185*	-.130**	.223**	.072	.690**
		Warsaw Pact			
Hungary	.498**	0	NA	-.203*	.651**
Soviet Union	.568**	NA	0	.156*	.884**
Bulgaria	.277**	.608**	0	-.073	.672**
Czechoslovakia	.547**	0	0	.286**	.566**
E. Germany	.692**	.643**	.338**	.07	.831**
Poland	.306**	.526**	.309**	.251**	.072
Romania	-.166	.909**	0	-.192*	.584**
		NATO			
Denmark	-.150	0	NA	.639**	.354**
United States	-.006	NA	0	.450*	.880**
Belgium	.145	-.211**	.127*	.658**	.777**
Canada	-.367	.269*	-.202*	.688**	.922**
France	-.006	0	0	.464**	.911**
W. Germany	-.466	-.228*	0	.482*	.501**
Italy	.675**	0	0	-.014	.486**
The Netherlands	.178**	-.152**	0	.411**	-.264*
Norway	-.184	0	0	1.090**	.504**
United Kingdom	.020	0	0	.285**	.798**

[a]Based on log-linear specifications. Each model also contains an intercept which is not reported.
*Significant at .10 level.
**Significant at .05 level.
NA—not applicable.

Sandler [1984] and Murdoch, Sandler, and Hansen [1991]. With the exception of Romania, the income elasticities in Table V are positive and less than one. The spillin terms are generally significant. Moreover, three of the seven estimates on enemy expenditures, *THREAT*, are positive and significant—a finding which is consistent with arms race behavior. Hungary's and Romania's $THREAT_t$ coefficients are, however, negative and significant. We feel that the theoretical structure is appropriate for the Warsaw Pact allies.

The evidence suggests that the extreme cases of weakest-link and best-shot models are probably inappropriate for the Warsaw Pact. Moreover, the lack of autonomy of the member nations, other than the Soviet Union, raises questions about members' ability to behave independently as required by collective-action models such as best shot. In general, the propensity to match the spending of the best shooter most likely reflects the high degree of central planning in this alliance and the private benefits to the Soviet Union derived from the spending by its allies.

The NATO alliance results are inconclusive and in many ways similar to the Warsaw Pact. The test statistics presented in Table IV show that Denmark is the only country clearly behaving as a weakest-link ally. Since Denmark is the weakest-link in terms of military expenditures, the test simply demonstrates that U.S. military expenditures are not significant in the Danish model.

There is some evidence in favor of best-shot behavior in the results for the U.S., Belgium, Canada, West Germany, and the Netherlands. However, the closeness of the p-values to .10 in Belgium, Canada, and West Germany makes this classification rather arbitrary. For France, Italy, Norway, and the U.K. neither the coefficient on $WEAK_t$ nor BS_t was significant in the unrestricted model.

The NATO findings seem to suggest a summation type of spillin technology. Since this technology has been analyzed quite extensively for the NATO allies, we refer the interested reader to Murdoch and Sandler [1984], Murdoch, Sandler, and Hansen [1991], and Hansen, Murdoch, and Sandler [1990] for a discussion of similar results. In general, the basic demand model specification fits the NATO alliance in terms of income and spillin terms. For convenience, Table V reports maintained model coefficient estimates for NATO. The prevalence of summation-type ally behavior over either best-shot or weakest-link behavior may indicate that both are present and mutually offsetting. Though there is an incentive to free ride on the best shooter, the increasing reliance on conventional force tactics from the early 1960s may have led both the weak-link and other allies to engage in matching behavior voluntarily (to distinguish it from involuntary matching in the Warsaw Pact.)

VI. CONCLUDING REMARKS

The public good approach to analyzing military alliances has become considerably more sophisticated since the early cross-sectional tests on NATO in the 1960s. The literature progressed to distinguishing private and public aspects of alliances, and then to more appropriate time-series models. This paper takes the discussion a step further by disaggregating the responses of allies to one anothers' military efforts, thereby allowing us to test for the presence of weak-link and best-shooter behavior.

The empirical results provide some evidence that the defensive Triple Entente behaved in a manner consistent with the weakest-link model when private joint products are included. In contrast, the offensive Triple Alliance displayed behavior more in agreement with the best-shot model and the existence of private benefits. Neither the Warsaw Pact nor NATO appeared to be characterized by either extreme case for the periods examined. The Warsaw Pact and NATO may be more appropriately classified as alliances whose members responded to the aggregate efforts of all their allies. Both alliances may have had offsetting mixtures of best-shot attributes (viz., the existence of a large core state providing a quasi-public good of nuclear deterrence) and weak-link characteristics (viz., a movement toward reliance on conventional forces, making the weak link more salient).

Best-shot and weak-link behaviors may well be found in other alliances. The Arab coalition against Israel and the pre-World War II alignments against Germany should be amenable to similar analysis. Most important, our procedure and test can be applied to other collective-action problems.

REFERENCES

Beach, Charles M., and James G. MacKinnon. "A Maximum Likelihood Procedure for Regression with Autocorrelated Errors." *Econometrica*, February 1978, 51–58.

Bliss, Christopher J., and Barry Nalebuff. "Dragon-Slaying and Ballroom Dancing: The Private Supply of a Public Good." *Journal of Public Economics*, July 1984, 1–12.

Brada, Josef C., and Ronald L. Graves. "The Slowdown in Soviet Defence Expenditures." *Southern Economic Journal*, April 1988, 969–84.

Bruce, Neil. "Defense Expenditures by Countries in Allied and Adversarial Relationships." *Defence Economics*, May 1990, 179–95.

Conybeare, John A. C., and Todd Sandler. "The Triple Entente and the Triple Alliance 1880–1914: A Collective Goods Approach." *American Political Science Review*, December 1990, 1197–1206.

Cornes, Richard. "Dyke Maintenance and Other Stories: Some Neglected Types of Public Goods." *Quarterly Journal of Economics*, February 1993, 259–71.

Cornes, Richard, and Todd Sandler. *The Theory of Externalities, Public Goods, and Club Goods*. New York: Cambridge University Press, 1986.

Crafts, N.F.R. "Gross National Products in Europe 1870–1910: Some New Estimates." *Explorations in Economic History*, October 1983, 387–401.

Dudley, Leonard, and Claude Montmarquette. "The Demand for Military Expenditures: An International Comparison." *Public Choice*, 37(1), 1981, 5–31.

Hansen, Laurna, James C. Murdoch, and Todd Sandler. "On Distinguishing the Behavior of Nuclear and Non-Nuclear Allies in NATO." *Defence Economics*, January 1990, 37–55.

Harrison, Glenn W., and Jack Hirshleifer. "An Experimental Evaluation of Weakest Link/Best Shot Models of Public Goods." *Journal of Political Economy*, February 1989, 201–23.

Hirshleifer, Jack. "From Weakest-Link to Best-Shot: The Voluntary Provision of Public Goods." *Public Choice*, 41(3), 1983, 371–86.

International Monetary Fund. *International Financial Statistics Yearbook*. Washington, D.C.: International Monetary Fund, various years.

Judge, George G., R. Carter Hill, William E. Griffiths, Helmut Lutkepohl, and Tsoung-Chao Lee. *An Introduction to the Theory and Practice of Econometrics*, 2nd ed. New York: John Wiley and Sons, 1988.

McGuire, Martin C. "Mixed Public-Private Benefit and Public-Good Supply with Application to the NATO Alliance." *Defence Economics*, January 1990, 17–35.

McGuire, Martin C., and Carl H. Groth. "A Method for Identifying the Public Good Allocation Process within a Group." *Quarterly Journal of Economics*, Supplement 1985, 915–34.

Mitchell, Brian R. *European Historical Statistics*. New York: Columbia University Press, 1975.

Murdoch, James C., and Todd Sandler. "Complementarity, Free Riding, and the Military Expenditures of NATO Allies." *Journal of Public Economics*, November 1984, 83–101.

Murdoch, James C., Todd Sandler, and Laurna Hansen. "An Econometric Technique for Comparing Median Voter and Oligarchy Choice Models of Collective Action: The Case of the NATO Alliance." *Review of Economics and Statistics*, November 1991, 624–31.

Okamura, Minuro. "Estimating the Impact of the Soviet Union's Threat on the United States-Japan Alliance: A Demand System Approach." *Review of Economics and Statistics*, May 1991, 200–7.

Olson, Mancur, and Richard Zeckhauser. "An Economic Theory of Alliances." *Review of Economics and Statistics*, August 1966, 266–79.

Oneal, John R., and Mark A. Elrod. "NATO Burden Sharing and the Forces of Change." *International Studies Quarterly*, December 1989, 435–56.

Sandler, Todd. "Impurity of Defense: An Application to the Economics of Alliances." *Kyklos*, 30(3), 1977, 443–60.

Sandler, Todd, and John F. Forbes. "Burden Sharing, Strategy, and the Design of NATO." *Economic Inquiry*, July 1980, 425–44.

Sandler, Todd, and James C. Murdoch. "Nash-Cournot or Lindahl Behavior?: An Empirical Test for the NATO Allies." *Quarterly Journal of Economics*, November 1990, 875–94.

Statesman's Yearbook. *Statesman's Yearbook*. London: Macmillan, 1879–1914.

Stockholm International Peace Research Institute. *World Armaments and Disarmament: SIPRI Yearbook*. New York: Crane, Russak and Co, various years.

U.S. Arms Control and Disarmament Agency. *World Military Expenditures and Arms Transfers*. Washington, D.C.: U.S. Government Printing Office, various years.

United States Congress, Joint Economic Committee. *Allocation of Resources in the Soviet Union and China*. Washington, D.C.: U.S. Government Printing Office, 1981, 1986–1988.

Van Huyck, John B., Raymond C. Battalio, and Richard O. Beil. "Tacit Coordination Games, Strategic Uncertainty, and Coordination Failure." *American Economic Review*, March 1990, 234–48.

van Ypersele de Strihou, Jacques. "Sharing the Defence Burden Among Western Allies." *Review of Economics and Statistics*, November 1967, 527–36.

Vicary, Simon. "Transfers and the Weakest Link: An Extension of Hirshleifer's Analysis." *Journal of Public Economics*, December 1990, 375–94.

Weber, Shlomo, and Hans Wiesmeth. "Economic Models of NATO." *Journal of Public Economics*, November 1991, 181–97.

Wong, Kar-yiu. "Foreign Trade, Military Alliance, and Defence-Burden Sharing." *Defence Economics*, April 1991, 83–103.

THE 1985–86 OIL PRICE COLLAPSE AND AFTERWARDS: WHAT DOES GAME THEORY ADD?

JAMES M. GRIFFIN and WILLIAM S. NEILSON*

This paper focuses on the strategies used by OPEC to generate cartel profits over the period 1983–90. The evidence supports the hypothesis that OPEC adopted a swing producer strategy from 1983 to 1985. But when Saudi Arabia's profits fell below the level of Cournot profits in the summer of 1985, it abandoned the role of swing producer, driving prices to the Cournot level. Subsequently, Saudi Arabia appears to have adopted a tit-for-tat strategy designed to punish excessive cheating by other OPEC members. Based on these findings, the strengths and limitations of game theory are assessed.

I. INTRODUCTION

Between August 1985 and August 1986, crude oil prices plummeted from $28 per barrel to $8 per barrel before stabilizing at $18 per barrel in the fall of 1986. Traditional oligopoly theory explanations point to the inherent fragility of cartel agreements due to the proclivity to cheat. While the tendency to cheat may be the correct explanation, these theories do not take us very far in answering the following deeper set of questions: Why do some cartels expire quickly while others tend to be long-lived? Alternatively, why do we observe price collapses under one set of conditions and not others?

The purpose of this paper is to consider whether game theory can help to motivate richer behavioral hypotheses which enhance our ability to answer this deeper set of questions. OPEC and the world oil market offer a particularly fascinating arena within which to test the applicability of game theoretic models. Because of the enormous complexity of this market, models of OPEC behavior must necessarily be incomplete. For example, because oil is a non-renewable resource, important complications of user costs arise, as in Pindyck [1985], along with issues of dynamic consistency, as in Newbery [1981]. Furthermore, the existence of a backstop fuel implies a price ceiling and a finite time period over which OPEC can manipulate price. Behaviorally, OPEC countries do not fit neatly into either a monolithic cartel model or the dominant firm/competitive fringe models that are so appealing because of their tractability, as shown by Griffin [1985] and Geroski, Ulph, and Ulph [1987].[1] Yet a further complication is the existence of a large non-OPEC competitive fringe, as discussed by Salant [1976], which supplies roughly one-half of world oil consumption.

In tailoring game theoretic models to particular market phenomena, one must

* Professor, Texas A&M University, and Associate Professor, Texas A&M University. We wish to thank Michael Baye, John Van Huyck, Steven Wiggins, Rodney Smith, and the referees for helpful comments. Larry Vielhaber and Weiwen Xiong provided excellent research assistance.

1. For example, Griffin [1985] tested a variety of OPEC behavioral models and showed that with the exception of Iraq (which behaved competitively), OPEC countries appear to follow some variant of a partial market sharing model over the period 1972 to 1983. Interestingly, OPEC countries appear to have been partially sharing markets well before official production quotas were first announced in 1982.

Economic Inquiry
Vol. XXXII, October 1994, 543–561