Pollution reduction management: The map of feasible coalition solutions

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Abstract**—**The paper is a contribution to solving such problems of pollution reduction management, where there are multiple polluters located in a territory. They have a choice to contribute to the goal of pollution reduction or with individual projects or with coalition projects. There is a standard requirement to achieve cost-effective (optimal) solution or, especially from the practical decision point of view, to realize some "second best" solution, i.e. solution which costs are not too much higher than the costs of the optimal variant. The model of reverse combinatorial auctions can serve as a theoretical basis for searching such solutions. The paper develops the model of the reverse combinatorial auction further, when presenting algorithm of calculation of all feasible coalition solutions. The result is labelled "map of feasible coalition solutions. The potentials of such the map for support of practical decision making about specific environmental protection investment programs and ideas how the map could be used for building background models with better controlled parameters for economic laboratory experiment for developing theory in the respective area are discussed at the end of the paper.

Keywords**—**Cost-effectiveness, environmental management, optimization, reverse combinatorial auctions, map of solutions.

I. INTRODUCTION

SOLUTION of problems of cost-effective environmental pollution reduction may come across situations where there are multiple polluters in an area and where interchangeable solution options consist in the option to implement pollution reduction projects at all polluters individually or achieve the same objective by using various combinations of joint projects.

In simple cases, optimal solutions can be identified intuitively (without complex calculations). In more complex cases, optimisation calculations are necessary with the aid of a computer and appropriate software. A typical example of this type of situation is the goal to radically reduce pollution (e.g., by phosphorus) entering a drinking water reservoir or recreational reservoir from (numerous, smaller) municipalities situated on the watercourses upstream of the inlet. The proposed methodology can serve well in solving other problems, where policy focuses more closely on solving problems in river sub-catchments [1] and where it frequently goes beyond Directive 2000/60/EC [2] and which involve decentralised solutions to such problems [3].

The paper first briefly introduces the reverse combinatorial auction model, which establishes a theoretical starting point for such optimising calculation as well as better understanding of polluters' behaviour in identifying solutions in practice. After that, it describes properties of so-called maps of feasible coalition solutions and the formalised procedure for calculating it.

The following chapter shows an illustrative example of such a calculation on a simple situation of a watercourse being polluted by four polluters.

The conclusion briefly discusses the potential benefits of the Map for support to practical decision-making as well as for research in the area, particularly the significance of the Map for compiling a background model for economic laboratory experiments.

II. REVERSE COMBINATORIAL AUCTION MODEL

We made an optimisation calculation for the feasible individual and coalition project designs that were approved. The objective is to identify a combination of individual and coalition projects that will enable the most cost-efficient pollution reduction targets for the watercourse.

The problem solution is grounded in the reverse combinatorial auction model. The reverse combinatorial auction problem is characterised by one buyer (here, an environmental authority) and several sellers (here, polluting municipalities). The utility of the model is that the quantities of both polluters and projects can be very high, whereby intuitive identification of the optimal solution is rather difficult. For more details about combinatorial auction theory see [4], [5]; for the initial idea of application of combinatorial auction theory on environmental problems see [6].

The buyer attempts to buy at least the required set of items from the sellers at minimum costs. Let us assume that m potential sellers S_1, S_2, ..., S_m are offering the set R with r items, $j = 1, 2, \ldots, r$, to the one buyer B.

This work was supported by the Czech Science Foundation, grant no. 13-07036S "Modelling of Negotiations in Environmental Policy under Information Asymmetry".

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The bid b_h made by the seller S_h, $h = 1, 2, \ldots, m$, is defined as

$$b_h = \{C, c_h(C)\}, \tag{1}$$

where

$C \subseteq R$ is a combination of items,

$c_h(C)$ is the price offered by the seller S_h for the combination of items C.

The purpose is to minimise the buyer's costs given the bids made by sellers. Constraints establish that the procurement provides at least a set of all items.

Binary variables are introduced for model formulation:

$y_h(C)$ is a bivalent variable specifying whether the combination C is purchased from the seller S_h, $y_h(C) = 1$.

The reverse combinatorial auction can be formulated as follows:

$$Z = \sum_{h=1}^{m} \sum_{C \subseteq R} c_h(C) y_h(C) \rightarrow \min \tag{2}$$

subject to

$$\sum_{h=1}^{m} \sum_{C \subseteq R} y_h(C) \geq 1, \quad \forall\, j \in R, \tag{3}$$

$$y_h(C) \in \{0,1\}, \ \forall \ C \subseteq R, \ \forall\, h, h = 1, 2, \ldots, m. \tag{2}$$

The criterion function Z expresses the objective, i.e., minimisation of the buyer's (authority's) costs. The restriction ensures the purchase of the required set of items.

Nevertheless, the optimum result can be calculated knowing the cost information determined by an expert estimate. Various solvers for bivalent programming tasks can be used. The CRAB (CombinatoRial Auction Body) Software System was used for calculating the results presented in this paper [7].

III. MAP OF FEASIBLE COALITION SOLUTIONS

A. Attributes of the map

The Map of feasible coalition solutions:

- It is an arrangement of all feasible solutions to the problem from the optimal option to the least cost-effective option.
- The feasibility criterion is that the option contains each component exactly once.
- The optimality criterion is minimisation of variously defined costs of acquiring variously defined benefits (here, social costs required for reduction of pollution).
- No other feasible option exists between neighbouring options in the map (arrangement).
- A special case of the map is a situation where there is no solution more effective than a set of individual solutions.

The map can be considered for all theoretically possible coalition solutions (combinations). However, the theoretical number of possible coalitions is very high even with not very many entities (there could be $2^n - 1$ coalitions, where n is a number of subjects). In practice, nevertheless, it is quite obvious to an expert sight of a significant proportion of the coalitions that they cannot be a part of a cost-effective solution. Therefore, a subset of theoretical coalitions is made (expertly) for which expert cost estimates are carried out and optimisation calculations made, including calculation of the map.

B. Calculation procedure

The optimal solution is computed by solving the problems (2) - (4). We get the so-called first-best solution. The optimal costs are denoted Z_1.

The map is represented by a list of feasible solutions ordered by effectiveness/costs of achieving goals.

The second-best solution is computed by solving the problems (2) - (4) with adding a constraint:

$$\sum_{h=1}^{m} \sum_{C \subseteq R} c_h(C) y_h(C) \ \geq \ Z_1 + \varepsilon, \tag{5}$$

where ε is a small positive value. The costs for the second-best solution are denoted Z_2. This procedure is repeated for the other ordered solutions.

Generally, we get the i-th solution by solving the problems (2) - (4) with adding a constraint

$$\sum_{h=1}^{m} \sum_{C \subseteq R} c_h(C) y_h(C) \ \geq Z_{i-1} + \varepsilon \,. \tag{6}$$

IV. ILLUSTRATIVE EXAMPLE

The authors made the Map calculation for the case study "Powder Brook", based on a practical situation in the Elbe river catchment in the Czech Republic. Its main objective was to test behaviour of polluters when elaborating applications for public (funding) support for individual or joint projects leading to a target reduction in the watercourse pollution. For more details on the case see [8].

There are 4 polluters (A, B, C and D) in the Powder Brook catchment area. The amounts of pollutants discharged in the Powder Brook catchment area have to be reduced significantly. Since these four polluters are located close to one another, it is conceivable to build both individual wastewater treatment plants and several combinations of joint wastewater treatment plants.

Experts knowledgeable about the situation selected 11 out of the 15 possible coalitions (24-1), including individual solutions, and carried out an expert estimate of related costs for each of them. These coalitions, including their total one-off costs, are shown in Table 1. The one-off costs shown in Table 1 include costs of constructing the waste water treatment plant (WWTP), sewerage system and other facilities.

Project no.	Project title	Total one-off costs
Individual projects		
1.	A	6,500
2.	B	16,250
3.	C	29,000
4.	D	32,750
Multiple coalition projects		
1.	AB	27,750
2.	BC	41,750
3.	CD	65,000
4.	ABC	50,000
5.	BD	59,000
6.	BCD	69,000
7.	ABCD	73,000

Fig. 1: Estimated costs of projects (CZK thousand)

Order	Coalition structure	Total one-off costs	Deviation [%]
1.	(ABCD)	73,000	0
2.	(BCD) A	75,500	3.4
3.	(BC) A, D	81,000	11.0
4.	(ABC) D	82,750	13.3
5.	A, B, C, D	84,500	15.8
6.	(CD) A, B	87,750	20.2
7.	(AB) C, D	89,500	22.6
8.	(AB)(CD)	92,750	27.1
9.	(BD) A, C	94,500	29.5

Fig. 2: Computed Map of feasible coalition solutions

Table 2 clearly shows the resulting map of solutions. The calculation identified 9 feasible coalition solutions. The optimum (cost-effective) solution is the joint construction of a WWTP by all the four polluters. It translates into a saving of approximately 16% of the costs compared to the option of separate WWTP for each. Furthermore, Table 2 shows the "deviation" of costs of the ordered feasible solutions. The second-best solution is associated with costs 3.4% higher compared to the optimum solution, etc. The last four coalition solutions are more expensive than construction of individual WWTPs. The difference between the costs of the optimum solution and those of the last feasible one is almost 30%.

For the sake of completeness, we also quote the remaining theoretically possible solutions, which were not included in the assessment by the experts and for which the costs were not estimated: (ABD) C; (ACD) B; (AC)(BD); (AD)(BC); (AC) B, D; (AD) B, C.

V. DISCUSSION AND CONCLUSION

A. Practical implications

If experts working as consultants for governmental institutions are capable of making relatively accurate estimates of primarily the cost parameters of proposed coalition solutions, the Map of feasible coalition solutions can be an aid in support to centralised (political) decision-making on solving a specific problem/case. Thus, the Map illustrates on the example how less effective the "second-best, third-best, etc., solutions are in the case that the optimal one is difficult to enforce politically, for instance due to mutual animosity between some neighbouring municipalities, which could otherwise save costs by jointly building and operating a wastewater treatment plant.

Good expert estimate of parameters of such a Map for a specific problem, or problem type, also facilitates orientation in the degree of (social) effectiveness of solutions proposed "bottom-up", in our case, proposals by the polluting entities.

For which policy decision-making model the Map will be used depends on the specific institutional setting (understood as both formal and informal rules of entities' conduct) in a given country or region.

The Map parameters may vary for a specific (practical) case over time. Experts or other players in solving specific problems may promote other coalitions into the solution, which then require respective cost estimates and new calculations. In addition, the Map may change with changing estimates of cost items of previously included coalition solutions. New calculations are also required in this case.

B. Implications for environmental economics and policy theories

The Map is used for acquiring better control over the parameters of background models serving economic laboratory experiments for testing various hypotheses or practical institutional/policy settings. For laboratory experiments building on data used in the Map calculation illustration in this paper, see [8]. Among other things, these calculations may verify hypothesis on entities' behaviour inferred from various findings of game theory. For more details see[9], [10]. For a comprehensive literature review, see [11].

If it is possible in future to carry out a certain typology of problems potentially solvable using combinatorial projects (requires a comparative analysis of a corresponding number of case studies, which is not available in the Czech Republic at the moment), we will be able to better formulate relevant policies/institutional arrangements, such as rules for allocating public support to entities for pollution reduction. [12].

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