Environmental modelling with reverse combinatorial auctions: CRAB software modification for sensitivity analysis

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Introduction

- The paper builds on work published in ISESS 2013 and in ISESS 2015:
  - the general model of reverse combinatorial auctions and its selected environmental applications
  - results of laboratory experiments showing whether and to what extent the negotiating parties at auctions are able to approach the optimal result.
- The main practical goal of the paper was to contribute to increased cost-effectiveness of waste water cleaning projects in conditions where coalition solutions are possible.
- The previous research results have shown the need to deepen our research into sensitivity analysis of the resulting optimal solutions. Specifically, in terms of understanding how to study coalition structures in the space between the optimal solution and solutions in the form of individual projects, and how the change of feasible coalition structures changes achieved cost.
- This paper provides an approach for calculating the sensitivity and proposals for necessary adjustments of CRAB software, which makes its use for the relevant decision-making tasks more user friendly.

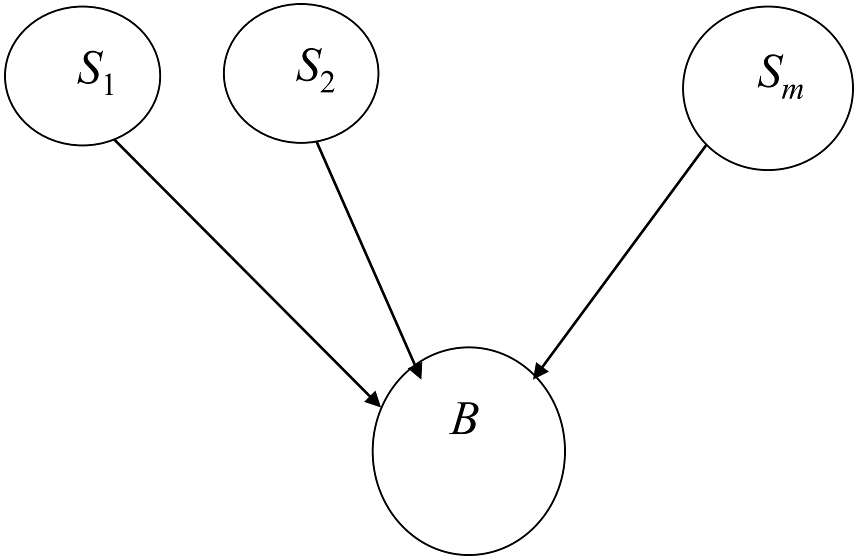
Reverse combinatorial auctions

- Supposed that m potential sellers S_1, S_2, ..., S_m offer a set R of r items, j = 1, 2, …, r, to one buyer B; a bid made by the seller S_h, h = 1, 2, …, m,

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

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

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

- 

Basic model of reverse combinatorial auction

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

subject to

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

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

- Bivalent variables are introduced for model formulation:
  $y_h(C)$ is a bivalent variable specifying if the combination C is bought from seller S_h ($y_h(C) = 1$).

- The objective is to minimize the cost of the buyer given the bids made by sellers.
- Constraints establish that the procurement provides at least set of all items.

Model with environmental standards

- This basic model only considers the minimisation of costs, which is complemented by restrictions on environmental standards.
- inequalities are added that compare the pollution reduction achieved with the required limit values for five specific environmental parameters.

$$\sum_{h=1}^{m} \sum_{C \subseteq R} e_{hi}(C)\; y_h(C) \;\geq\; E_i$$

where e_{hi} are pollution parameters of the projects and Ei are the prescribed environmental standards for the parameters.

Sensitivity analysis

- For small examples it is possible to compute and relatively easily analyse all solutions, with coalition structures from the first best (optimal) solution ranked by increasing cost.
- The optimal solution is computed by solving the basic model The optimal costs are Z1.

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

- In typical practical cases, the number of feasible coalition structures is huge. For this reason, it is not possible to analyse all of them individually.
- We propose sensitivity analysis based on analysing coalition structures for specific cost levels, can still provide support for decision-making about the projects in such cases. The difference between costs for individual project structures and costs for the first best solution could be divided to several levels corresponding to politically acceptable deviations of the practical program from the first best solution.

$$\sum_{h=1}^{m} \sum_{C \subseteq R} c_h(C) \ y_h(C) \geq L_i , \ i = 1, 2, \ldots, n,$$

where n is number of levels and L_i are cost levels.

CRAB software

- CRAB is a non-commercial software system for generating, solving, and testing combinatorial auction problems.
- The system solves problems using Balas’ method or the primal-dual algorithm .
- CRAB generates problems fast; combinations are generated in a more predictable way and only in given subset of all items; CSV is used as the primary data format; there is fine-grained control over the generated problem; a linear problem solver is a part of CRAB; and it provides multiple output formats.
- CRAB is implemented in Ruby, which enables us to quickly experiment with different approaches.
- The user of CRAB software can change automatically generated constraints and add or remove additional ones. The problem can be passed to the built-in binary programming solver to find out the optimal solution for a given combinatorial auction. Afterwards, the transformed model is passed to the Balas algorithm.
- The CRAB architecture provides the possibility of extending the system, especially with respect to the implemented models and algorithms. For the sensitivity analyses, we modified the CRAB software according to the approaches for sensitivity analysis.

Practical cases

- In practical cases, there are a large number of polluters, thus creating more complex models and calculations. In such cases, there are a large amount of feasible solutions. These situations can be solved in two ways:

  - In some cases, the solution of the entire case is divided into optimisation problems of sub-segments of river basin. A typical example is in a mountainous area, where it is possible to optimise the construction of wastewater treatment plants for each valley. For this situation, see the numerical example.
  - If this is not possible, then one can work with "levels" between the cost of first best (optimal) solution and the cost of individual projects.

Example

Project	Participated municipalities	Project costs
Individual projects		
1.	A	7500
2.	B	18000
3.	C	31000
4.	D	28000
Coalition projects		
1.	AB	27750
2.	BC	41750
5.	BD	59000
3.	CD	65000
4.	ABC	45000
6.	BCD	69000
7.	ABCD	82750

Sensitivity analysis by CRAB

1st Solution (=first best)
Total cost: 73000.00
Coalition structure:
One 1-member coalitions: D
One 3-members coalitions: ABC

2nd solution Total cost: 76500.00 Coalition structure: 1-member coalitions: A 3-member coalitions: BCD	6th Solution Total cost: 86750.00 Coalition structure: 1-member coalitions: C,D 2-member coalitions: AB
3rd Solution Total cost: 77250.00 Coalition structure: 1-member coalitions: A,D 2-member coalitions: BC	7th Solution Total cost: 90500.00 Coalition structure: 1-member coalitions: A,B 2-member coalitions: CD
4th Solution Total cost: 82750.00 Coalition structure: 4-member coalitions: ABCD	8th Solution Total cost: 92750.00 Coalition structure: 2-member coalitions: AB, CD
5th Solution Total cost: 84500.00 Coalition structure: 1-member coalitions: A,B,C,D	9th Solution (least efficient solution) Total cost: 97500.00 Coalition structure: 1-member coalitions: A,C 2-member coalitions: BD

Lake Rozkoš

- Lake Rozkoš is located in the Elbe River basin in Bohemia. Two scenarios for achieving environmental targets (required status of the lake water) were formulated by specialists, together with an assessment of the investment and operating costs of the projects. The optimal solution (investment program) for 41 polluter-municipalities, where 166 coalitions were considered (41 individual WWTPs and 125 joint WWTPs), was computed. The results of the optimisation modelling presented in this paper have shown that over 20% of the costs could be saved where selected joint WWTPs are realised.
- A sensitivity analysis was performed. Since the number of feasible coalition structures is huge (there are 2^{166}), it would not be practical to analyse all of them. For this reason, the difference ("space") between costs for individual projects and costs for the first best (optimal) solution was initially divided into six levels corresponding to policy decisions about potential (politically acceptable) deviation of the practical program from the (theoretical) first best solution. The levels create borders of quintiles in the space of all potential solutions. Level 1 was defined as the cost for the first best solution, level 6 as the cost for individual projects. Other levels are always about 20 percent higher than the previous level, where the second level was suggested as the politically acceptable one. These calculations provided a useful picture for better assessment of potential projects submitted in the region.

Lake Pastviny

- Lake Pastviny is located in east Bohemia, near the Polish border. The initial set of projects aimed at achieving the environmental standards required for bathing water in Lake Pastviny consists of 24 individual projects (WWTPs) and 131 multiple-coalition projects. These included 32 two-member coalitions, 38 three-member coalitions, 38 four-member coalitions, and 22 five-to-eight-member coalitions. The abatement costs, in the form of investment and operating costs, were assessed by the specialists for all of these projects. The analysis indicated a potential saving of annualised abatement costs of 6% in the case where half of the municipalities located in the lake watershed join specific coalitions and the rest build an individual WWTP.
- In this case, the initial sensitivity analysis works with 4 costs levels. Level 1 was defined as the cost for the first best (optimal) solution, level 4 as the cost for individual projects. Other levels are always about 33 percent higher than the previous level. Moreover, here, the results provide a picture of how changing the coalition structure by decreasing of the number of multiple-member coalitions leads to an increase of the costs.

Conclusions

- The paper is devoted to modification of the CRAB software for sensitivity analysis of solutions to combinatorial auction problems. The modification is used for analyses of coalition projects for the building of WWTPs. We propose two possibilities.
- The first approach is appropriate for small examples, where it is possible to compute all feasible solutions ordered by total cost. In such cases, it is possible to analyse changes of coalition structures in terms of their increasing cost.
- The second suggested modification of the CRAB software makes it possible to analyse a high number of feasible coalition structures located between the optimal coalition (i.e. the cost-effective one) and the structure consisting of individual projects. This approach is appropriate for setting of cost levels in complex real applications, including multiple-round subsidy negotiations.
- The proposed approach of sensitivity analysis can be used not only in the case of reverse combinatorial auctioning in cleaning waste waters; the waste water treatment issue was used as a typical practical application.
- Two practical applications are presented in the paper, together with a discussion of their contribution to relevant decision-making processes. In both cases, it is possible to continue to more detailed sensitivity analysis, according to the concrete requirements of participants in the decision making process. This could be particularly useful when the projects are multiple-round negotiated with the authority and other stakeholders.

Thank you for your attention !