A DEVS-Based Study of Social Welfare Evolution in Iterative Combinatorial Double Auctions

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Abstract. Combinatorial double auctions provide an efficient mechanism for resource allocation, maximizing social welfare without requiring private information from participants. However, depending on specific auction conditions, the number of rounds required for convergence can be significantly high. In this work, we extend a previously developed DEVS-based auction model to study the dynamics of social welfare evolution throughout the auction process. While the original model identifies the allocation that maximizes social welfare, our extension enables tracking the proportion of the optimal social welfare achieved at each round. This analysis provides insights into the auction's convergence behavior and serves as the foundation for developing an approach that helps auctioneers select appropriate parameters to achieve a sufficiently good outcome within a reasonable number of rounds in real-world scenarios.

Keywords: Combinatorial Auction, DEVS, Social Welfare.

1 Introduction

Combinatorial auctions are effective tools for resource allocation, ensuring both efficiency and fairness while preserving participants' privacy. By allowing bids on bundles of goods or services rather than individual items, these auctions are particularly useful in markets requiring the combination of complementary resources, such as energy, telecommunications, and spectrum auctions [1]. This flexibility has extended their application to various allocation problems, including electric vehicle charging scheduling [2], machine task scheduling [3], mobile edge computing task offloading [4], and multi-prosumer energy sharing [5]. Recently, iterative combinatorial auctions have been explored for complex scenarios like assigning surgeons to operating rooms [6], distributing computational tasks to cloud servers [7], and optimizing client-provider allocation in procurement [8, 9].

Despite their advantages, iterative combinatorial auctions face challenges in practical implementation due to the high number of rounds required to achieve convergence and maximize social welfare—defined as the total utility of all participants. This issue complicates their application in real-world scenarios. Identifying optimal auction parameters that guarantee fast convergence is therefore crucial for enhancing the efficiency and feasibility of these auction mechanisms.

This paper builds on a formal DEVS (Discrete Event System Specification) model for a combinatorial double auction [10], where both buyers and sellers submit bids for combinations of items they wish to acquire or sell. While this model effectively addresses both allocation and pricing problems, the authors conclude that the number of rounds required to reach an acceptable level of social welfare is often high. The objective of this work is to extend the previously developed DEVS-based auction model to study the evolution of social welfare throughout the auction process. While the original model identifies the allocation that maximizes social welfare, the proposed extension tracks the proportion of the optimal social welfare achieved at each round. This analysis provides insights into the auction's convergence behavior and lays the foundation for developing an approach to help auctioneers select appropriate parameters to achieve a sufficiently good outcome within a reasonable number of rounds in practical scenarios.

The rest of the paper is organized as follows: Section 2 details the extension of the DEVS model for a combinatorial double auction. Section 3 presents the simulations conducted. Section 4 provides the discussion and conclusions of this work.

2 DEVS model

The Discrete Event System Specification (DEVS) is a hierarchical and modular formalism designed for modeling discrete event systems, enabling the composition of complex systems from simpler ones through modular coupling [11]. It employs a rigorous methodology that decomposes systems into atomic and coupled models, where atomic models define behavior and coupled models specify structure. Both types interconnect inputs and outputs, supporting the systematic construction of complex models.

The original Combinatorial Iterative Double Auction (CIDA) model proposed in [10] is a DEVS coupled model comprising three core components: *Buyer* (with multiple instances), *Seller* (with multiple instances), and *Auctioneer*. Represented in black in Figure 1, this initial CIDA model structures *Buyers* and *Sellers* as coupled models, each corresponding to an individual participant in the auction. These models decompose into two atomic components: *Buyer* consists of *Filter* and *Bid*, while *Seller* comprises *Filter* and *Ask*. The *Auctioneer* atomic model coordinates the auction process. During instantiation, *Buyer* and *Seller* instance counts are determined based on auction participation.

This auction model allows simulating the progression of an iterative combinatorial double auction in which the auctioneer collects buying bids (i.e., bids) on items from buyers and asking bids (i.e., asks) on bundles of items from sellers in each round and determines item allocation and pricing. Item allocations obtained at the end of each round will be temporary until, after a certain number of rounds, a final allocation is derived (once the termination condition is satisfied) and the auction is closed. Within this iterative procedure, the auction mechanism introduces a price-updating scheme to guide the advancement of the auction toward a final allocation that maximizes social welfare. This scheme is configured through a price step parameter, set at the beginning of the auction, which determines the amount that bids and asks excluded from a temporary allocation must be updated in the subsequent round.

While the current CIDA model effectively implements the iterative auction procedure to solve allocation and pricing, computational experiments revealed that a high number of rounds was necessary to derive a solution that captures a high portion of the social welfare. As the practical implementation of an auction in a real-world setting might benefit from a fast convergence, the CIDA model is extended to analyze the evolution of social welfare throughout the succession of rounds in the auction process. This is done by the *Analysis* atomic model displayed in red in Figure 1. The new atomic model is integrated into the previous *Auction* coupled model (i.e., the CIDA model) forming the extended *Auction_analysis* coupled model.

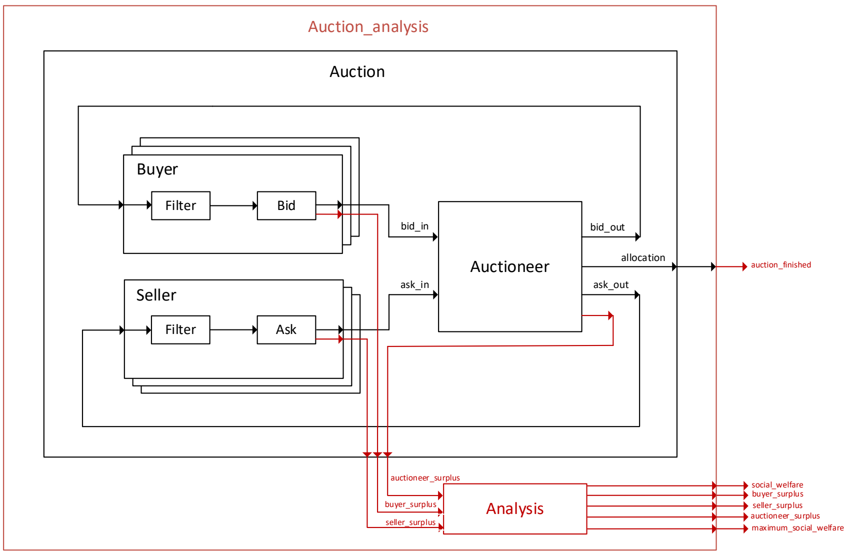

Fig. 1. DEVS model of a combinatorial double auction [10] in black, with the extension presented in this paper to analyze the auction dynamics in red.

The social welfare (or total surplus) of an auction is calculated as the aggregate surplus of all participants. In each round, the *Analysis* model collects the surpluses of buyers, sellers and the auctioneer based on the corresponding temporary allocation, calculates the total social welfare and determines the proportion of the maximum achievable social welfare attained in that allocation. Thus, *Analysis* tracks the proportion of the optimal social welfare captured in each round, providing insights into the auction's convergence behavior.

3 Simulation and results

This section presents the simulation experiments conducted to analyze the evolution of social welfare through the auction, using the extended auction model with the new analysis module. The simulation is designed to study the combined effect of the price step size on the convergence speed of the auction and the quality of the solution obtained in terms of social welfare attainment. Figure 2 presents the simulation outcomes of an auction instance executed using the DEVS extended model with seven different step sizes. The results will be analyzed in the remainder of the section.

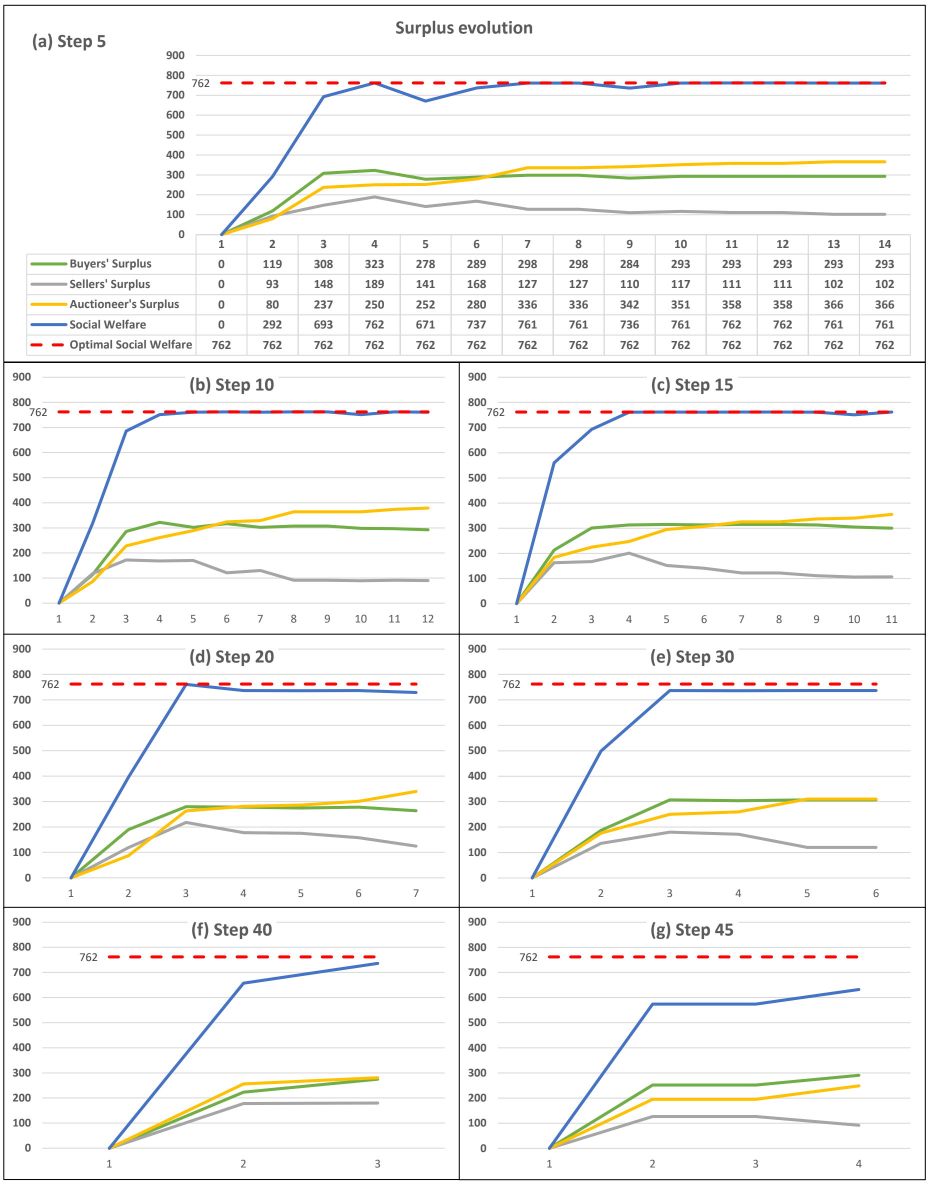

Fig. 2. Evolution of the surplus for buyers, sellers, the auctioneer, and all participants combined (social welfare) for different sizes of the price step parameter.

The selected simulation instance serves as a representative example of an auction scenario, consisting of 20 buyers and 20 sellers. The results of each simulation are displayed in a five-line chart that depicts the round-by-round surplus evolution of buyers (green), sellers (gray) and the auctioneer (yellow), the progression of the social welfare (blue) and the optimal social welfare (dashed red) as an upper bound.

The line charts reveal that, for lower values of the step size (e.g., steps 5, 10 and 15), the auction can attain the optimal (or close to the optimal) social welfare, but it needs a significant number of rounds to converge. On the contrary, higher step sizes (e.g., 40, 45) result in fewer auction rounds whereas the social welfare attained is far from optimal. These results indicate the potential existence of a most favorable step size that balances capturing a significant proportion of the optimal social welfare while ensuring rapid auction convergence.

4 Discussion and conclusions

In this paper, we analyze the evolution of the total welfare achieved by a combinatorial iterative double auction throughout its rounds. Our findings indicate that varying the step size from smaller to larger values influences two aspects of the auction's outcome:

- Speed of convergence: Increasing the step size allows the auction to reach the maximum total welfare in fewer rounds. However, beyond a certain point, this effect reverses. In fact, there is a step size so large that convergence becomes impossible, as the initial bid already exceeds the buyers' reservation prices (or falls below the sellers' production cost). In this scenario, no transactions occur in the market, and the allocation remains as initially determined by the opening bids.
- Proximity to the optimal solution: Smaller step sizes allow the auction to reach the optimal solution (or a level of social welfare very close to the optimal) but generally require a large number of rounds. As the step size increases, it becomes possible to achieve the optimum in fewer rounds. However, there is a threshold beyond which the total social welfare cannot be reached. This occurs because, with an excessively large minimum step size, the available margins from the last bid/ask to the reservation prices/production costs are not fully exploited.

Optimizing the practical implementation of this type of auction requires establishing a mechanism that, based on the initial known parameters of the auction (such as the initial bids of buyers and sellers or the level of overlap between the combinations of items sought by the sellers), enables the auctioneer to reliably estimate an appropriate minimum step size. This estimation should achieve an acceptable balance between obtaining high total social welfare, which benefits society as a whole, and limiting the auction to a reasonable number of rounds without sacrificing the attainment of the desired social welfare.

For this reason, future steps in this research will involve conducting the study on a set of instances, which will be generated and selected to exhibit different values for those initial parameters. Once the results confirm the proposed hypotheses (i.e., that there is evidence of an optimal minimum step size that enhances auction performance based on the two criteria discussed above), the next step will be to infer, from all simulated instances, a procedure (e.g., through function fitting) to estimate an appropriate minimum step size based on these parameters. The ultimate goal is to advance towards the real-world implementation of this type of auction.

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