Power Engineering Lab: Electricity Market Simulator

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***Abstract*—This paper presents a successful lab experience to teach pool-based electricity markets to power engineering students. Students are arranged in groups and assigned, at random, a set of generators. They play the role of power producers and compete against each other with the target of maximizing their own profits. The instructor plays the role of the market operator. A market simulator and a computer communication network make it possible to simulate the actual functioning of a pool-based electricity market. The elements that have made this educational experience successful are described and analyzed. Several case examples are discussed.**

***Index Terms*—Electricity markets, power engineering laboratory, power producers, simulation tool.**

I. Introduction

A. Background

In many countries all over the world the power industry is moving toward a competitive framework and a market environment is replacing the traditional centralized operation approach. The main objective of an electricity market is to decrease the cost of electricity through competition. The market environment typically consists of a pool and a floor to carry out bilateral contracts. Adequate new software tools are needed to support new activities in the pool, such as optimization-based generation schedulers and price-bidding tools. The pool, or power exchange (PX), is an e-commerce marketplace where generating companies (GENCOs) submit production bids and their corresponding prices and consumer companies (CONCOs) do the same with demand bids. The market operator (MO) uses a market-clearing tool to clear the market at every hour and this results in a market-clearing price and the set of accepted production and consumption bids. From a pool perspective, an appropriate market-clearing tool is a double auction mechanism [1]–[3]. Hourly auctions are performed one at a time and repair heuristics are used to make results technically feasible. Hourly adjustment markets are also used to take deviations into account and to repair infeasibilities.

It is crucial that students get exposed to the functioning of the electricity markets. Furthermore, the power industry is demanding an increasing number of power graduates with knowledge of the theoretical and practical foundations of electricity markets. Students need also to obtain practical experience on how to generate bids and on how to bid. One of the best ways to achieve this goal is by means of an electricity market simulator [4]–[6].

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B. Experience

This paper presents a successful lab experience in which students get familiar with all the steps that a power producer must perform to generate successful bids in an electricity pool. This experience has greatly increased the interest of students in power subjects, has promoted their creativity and has been a vehicle to cradle their innovative ideas. This lab experience is built around a market simulator. This simulator is based on the widely used software package MATLAB and a computer communication net, which can be replaced by the WWW. The experience has been carried out at the University of Castilla—La Mancha, Ciudad Real, Spain, as a part of a senior undergraduate course on power system analysis.

Students are divided into groups and every group is assigned, at random, a set of power plants, including their operational and cost characteristics. All sets of power plants are reasonably similar. Student groups behave as power producers and the instructor plays the role of the MO. The functioning of the PX is as follows.

1) The MO broadcasts hourly loads in an electronic bulletin board using the computer communication net or the WWW.
2) Every student group has a limited amount of time to derive its strategy as a power producer and to send its production and price bids to the MO using the computer communication network.
3) The MO clears the market and determines the hourly market-clearing prices and the revenues of every group which are made public through the electronic bulletin board.

Steps 1 to 3 reproduce the actual functioning of an electricity market based on a pool. This market simulation procedure is repeated several times. The first trials allow students to get familiar with the procedure and the last ones are used to rank and grade them. Fig. 1 depicts the e-commerce architecture of the proposed electricity market.

In order to derive an aggregate bidding strategy, students have two types of tools available. The first one is a price-forecasting package that allows them to forecast next-market clearing prices [7]. The second one is an optimization-based tool allowing student groups to determine the optimal response of any of their generators to a sequence of prices such that the profit of the generator is maximized. This tool is of the type reported in [8].

Unlike actual markets, the MO has also available operating constraints and cost information of every generator of each group. This makes possible to compute the profits of every group and therefore to rank and grade them. It also allows checking that no generator, when bidding, is violating its operational constraints.

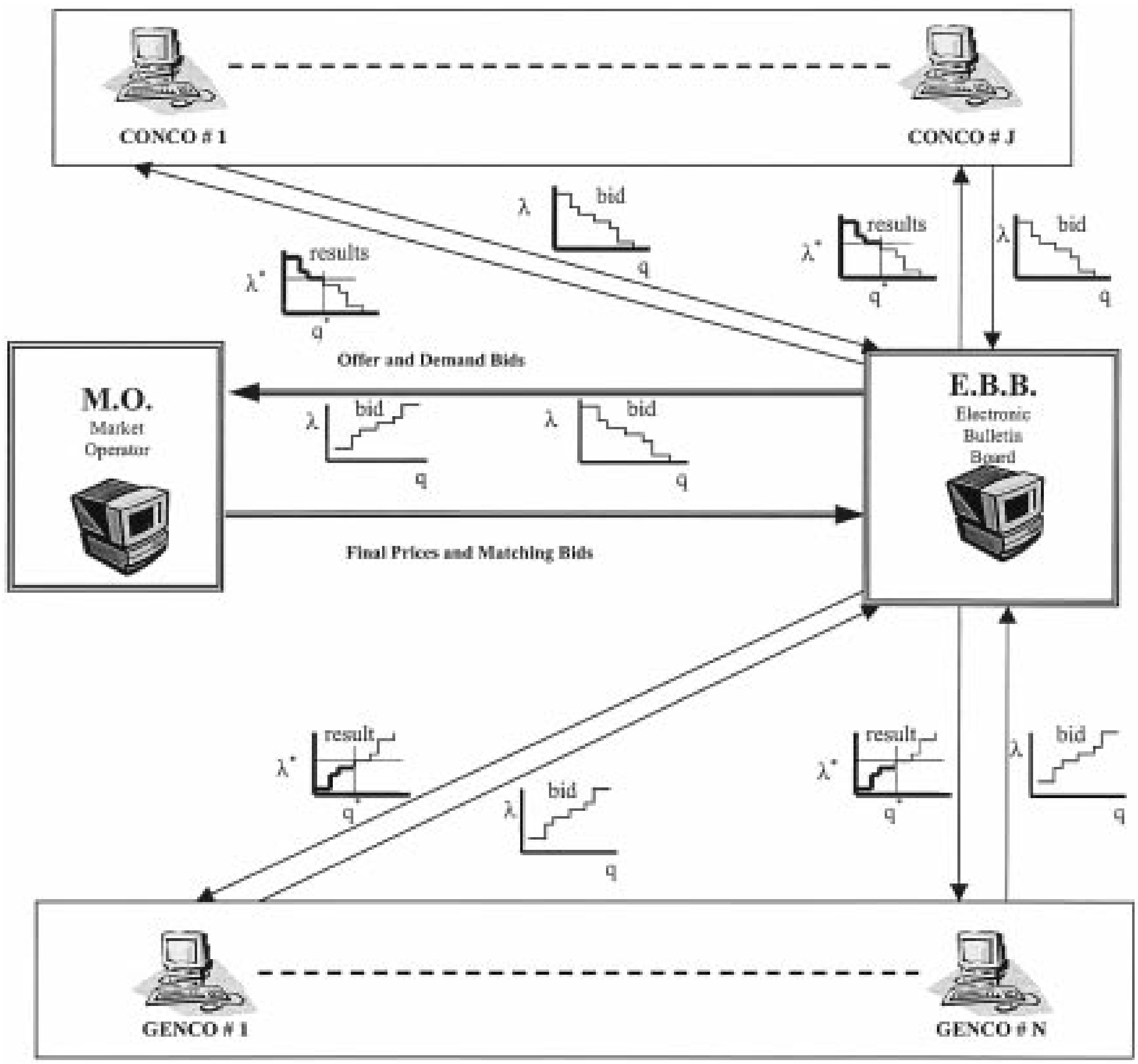

Fig. 1. Architecture of the market simulator.

II. ELECTRICITY MARKET SIMULATOR

As previously mentioned, the considered electricity market is a trading pool made up of groups of generators, demand(s), and a market operator that carries out the matching of bids.

The rules of this pool are inspired by the electricity market of mainland Spain [9] and they are described below. The interested reader can find an unofficial translation of these rules in English [10]. Additionally, the required MATLAB files and www plug-ins to run the simulation can be found in [11] and [12], respectively. The MATLAB files of the simulator, as well as the standard software used, are also available to the reader [11], [12].

In a single-period simple auction, the supply bids are matched with the demand bids by the market clearing algorithm. The time step to perform the matching of bids is 1 h. This type of auction is depicted in Fig. 2. The procedure is as follows. For each hour, a supply curve is built up considering the selling bids for that hour ordered by increasing prices and a demand curve is built up considering the buying bids for that hour ordered by decreasing prices. The intersection of the supply and demand curves determines the selling and buying bids that are accepted and the hourly market price obtained as the price of the last accepted selling bid.

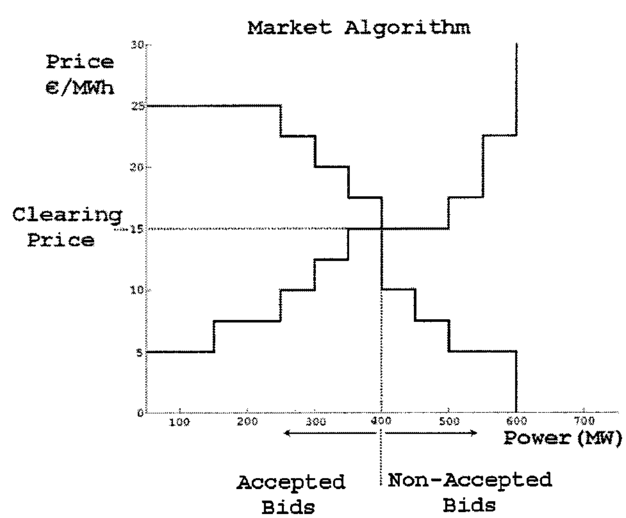

Fig. 2. Simple bid matching algorithm.

The simplest way to bid is using a "simple" bid format consisting of a pair of (hourly) values: quantity (MWh) and price (€/MWh). Each selling or buying participant can present several pairs of values for the same generation or demand unit. Groups are required to produce four-block bids for every one of its units in every hour.

However, in a realistic electricity market auction, it is necessary to consider constraints that bind time and production, technical constraints and also the economic concerns of the generating groups. Therefore, a more complex mechanism to match bids including some extra conditions from the bidders' side are required.

When bids are not "simple" but "complex," each production unit is allowed to bid with several extra conditions, in addition to the simple price/quantity bids.

- *Minimum Output Power*: The first quantity bid is always nondivisible. That is, in case that the designated bid is accepted, it should be for the total quantity and not for a fraction of it. This condition has been implemented to take into account that some thermal units have to run above a specified minimum operating level.
- *Up- and Down-ramp Rates*: The maximum variations of the unit output in two consecutive hours can be specified. That is, for the considered unit, the energy scheduled by the matching algorithm in two consecutive hours must meet the maximum variation condition specified as MW/hour for increasing output and/or MW/hour for decreasing output.
- *Minimum Up-time*: Once a thermal unit is on, it should be working for a given number of hours.
- *Minimum Revenue*: This condition is specified with a fixed term (in €) and a variable term (in €/MWh). The specified minimum revenue value (the fixed term plus the variable term times the sum of the dispatched energy) must be lower than the revenue which is obtained by multiplying the specified matched quantities and closing prices in the "simple" format of the considered generating unit bid.

Also, the matching of bids uses several repair heuristic algorithms. These algorithms fix infeasibilities that may appear because one or more constraints are unfulfilled. The matching of complex bids is as follows.

First, the matching algorithm considers all bids to be simple and produces prices that are not affected by any constraint. Then, there is a sequence of checkings of constraints and their corresponding repair algorithms. The order of the sequence follows.

- The MO checks if all the matched productions fulfill the up- and down-ramp rates. If a unit produces a quantity that is beyond its allowed production, this quantity is reduced to the up-ramp rate limit of this unit, starting from the unit most expensive bid. Similarly, if a unit is producing less than the down rate limit, its production is increased, starting with its own cheapest bid. This process is repeated for all time periods, starting from the previous hour bid curve at each period.
- The MO verifies if all generators have included the minimum output power condition in their bids. The noncompliant bids are ordered in an increasing fashion, depending on the quantity bid. Beginning with the smallest one, the noncompliant bids are withdrawn one by one and the process is repeated until all the remaining bids fulfill the constraint.
- The MO checks if any minimum up-time is not met by any unit. If so, the unit withdraws the market and the process is repeated until all the units meet the time condition. It may happen that when a unit leaves, another unit that did not comply with the constraint is able to return to the market.
- The MO verifies if every unit complies with the minimum revenue condition. Previously, the MO has calculated every unit revenue (closing prices times matched quantities). Then, it orders the units according to the difference between actual and minimum revenue, such that the unit with the biggest nonfulfillment is the first to leave the auction. The process is repeated for all time periods until all the units comply with the constraint. It is possible that a unit can re-enter the auction because, when another unit leaves the market, prices increase and it is possible that the revenue of the new entrant may increase.

Finally, there are additional tools available to the students to improve their bids, such as a price forecasting engine and an optimal response algorithm [8]. These tools are likely to be used by sophisticated or experienced bidders. When placing their bids, the students are aware of the optimal self-scheduling of their own units and they have updated information of the aggregated offer and demand curves. After a few rounds, they are experienced with the program and with their own previous successes and failures.

The price forecast engine uses time series data of hourly prices to forecast next-market prices. Student groups use a data-base of historical prices to forecast the clearing prices of the market they are facing. Once they have forecasted market clearing prices, they use them to determine the productions of their generators, facing these prices and meeting all technical constraints.

The target of every group is to maximize its profits. Student groups do that using an optimal response algorithm that provides for a given generator its optimal energy production in every hour. Using this information student groups should prepare their respective bidding strategies and perform the actual bidding using the computer communication network. Although market power is perfectly possible, game-theoretical negotiation strategies [13] exceed the scope of the market simulator. Nevertheless, the simulator can be used to simulate the behavior of price-makers as well as competitive fringe producers.

III. Case Studies

Five generators during a period of four hours with an elastic demand are considered in the following case studies. The considered cases are: a base case and two modifications designed to test the student's understanding of the whole problem.

The maximum and minimum power output for every unit are shown in Table I, where $P_{\min}$ is the minimum power output and $P_{\max}$ is the maximum power output.

Data regarding the bids for the five generators are presented in Table II, where P is the offered power in MW and λ is the price of the corresponding block in €/MWh. In this example, there are four blocks per generator, each one possibly different in amount and price.

TABLE I
GENERATOR DATA

	UNIT 1	UNIT 2	UNIT 3	UNIT 4	UNIT 5
P_{min} (MW)	7	10	8	9	20
P_{max} (MW)	197	210	163	74	290

The elastic demand is modeled using five demand blocks with prices in decreasing order. The demand blocks are shown in Table III, where D is the demand of every block in MW and λ is the price in ∈/MWh. Fig. 3 shows the matching of generation and demand bids for the first hour. Note that every student group is assigned a generator in all case studies, while the actual arrangement is five generators per group. For the sake of clarity, the number of units has been reduced in this illustrative example.

It should be noted that if the price-demand curve intersects the horizontal part of the price-production curve (as in Fig. 3), the demands consume up to their last MW demanded and accepted. However, the initially accepted bids of the marginal generators are proportionally shaved so that production and demand are balanced. Similarly, if the price-demand curve intersects the vertical part of the price-production curve, then the sharing would be on the demand side. That is, all generators would produce up to their last accepted MW, but initially accepted marginal demand bids would be proportionally shaved.

The way to measure the performance of every student group is by means of revenue comparison. At the end of the simulation the student group revenue, which is the product of all accepted bids times hourly prices, is made public. Students are rewarded according to their success in bidding.

A. Base Case Study

Total revenues are: 3968, 9579, 10618, 3502, and 18 735 ∈, respectively. Final prices for the four hour period are: 16.5, 18, 21 and 21 ∈/MWh, respectively. Final output of the units after closing the market are presented in Table IV.

From the results of Table IV it can be observed that, as long as units 3 and 5 do not offer prices above 18 ∈ /MWh in hours 3 and 4, the market allows them to produce their maximum power output. Unit 1 produces 0 MW in hour 1 because the price offered by the demand is 16.5 ∈/MWh and its lowest price bid is 18 ∈/MWh.

B. Second Case Study

The first modification of the base case study assumes that unit 3 has a ramp rate limit equal to 50 MW per hour. Resulting power outputs are now presented in Table V.

The total revenue of each unit becomes: 3979, 9698, 10265, 3532, and 18 929 ∈, respectively. Final prices for the four hour period are 16.5, 18, 21, and 21 ∈/MWh, respectively.

Note that in the base case unit 3 violated the ramp rate limit constraint between hours 1 and 2, as seen in Table IV. From Table V, unit 3 now has to decrease its production in hour 2 (as shown in shadow) in order to satisfy the ramp rate limit constraint and hence, its revenue decreases. The remaining units take advantage of that and increase their revenues.

C. Third Case Study

The second modification assumes that the first block is indivisible for unit 1 and that the ramp rate constraint of unit 3 is still enforced. Table VI shows the power output of the units.

The total revenues of the units are: 3871, 9736, 10265, 3541, and 18 990 ∈, respectively. Final prices for the four hour period are: 16.5, 18, 21, and 21 ∈/MWh, respectively.

Note that unit 1 did not meet the indivisibility constraint in the previous two cases. However, in the third case unit 1 cannot produce in hour 2, as indicated in shadow in Table VI. As expected, unit 1 decreases its revenue.

D. Comparison

From the three case studies some conclusions can be inferred. As shown in Fig. 4, if one additional constraint is added, those units that are affected by the constraint decrease their revenues and the units that are not affected increase their revenues. This is the case for units 2, 4, and 5 that are not affected by any of the constraints.

E. Summary

The previous examples have been proposed to students with the intention that they get exposed to the effect of ramp rates, minimum up- and down-times, and minimum power output constraints. They actually grasp the effect of these constraints and tend to bid consequently. After several round trials, they become aware of the limitations of their units. It has been observed that only successful (in terms of revenue) bid changes are kept in the following rounds.

IV. LAB EXPERIENCE

Previous to the lab work, students get familiar with the design and rules of the market they have to simulate in the lab. The market rules that have been used are those explained in Section II.

Students are arranged in groups of three. All groups are assigned five power units. More than five units makes data handling messy enough to distract students from their task as bid producers. The group only knows the cost and production characteristics of its units, not the characteristics of the units of other groups. In this way, every group becomes a power producer with no knowledge of its competitor data. The target of every group is to bid in the market to make more money that its competitors. The market time horizon is up to 5 h. This number of hours is sufficient to get students exposed to the effect of ramp-rate, minimum up-time and minimum down-time constraints.

Groups should produce four-block bids for every one of its units. Bidding prices should increase and the first bidding power block should be the unit minimum output power. To design the bids the group can used a price forecasting tool and an optimal response tool.

The actual lab experience follows the steps shown in the following.

1) The instructor (MO) broadcasts the hourly loads. Up to five hourly periods are considered. Longer market horizons make it difficult for students to derive appropriate answers.

TABLE II
GENERATOR BID AMOUNT (MW) AND BID PRICE DATA (€/MWH)

UNIT		HOUR 1				HOUR 2				HOUR 3				HOUR 4			
1	P	7	50	60	80	7	54	56	80	7	50	60	80	7	50	65	75
	λ	18	20.4	21	24	18	20.4	21	24	18	20.4	21	24	18	20.4	21	24
2	P	10	30	80	90	10	30	80	90	10	25	85	90	10	30	80	90
	λ	15	15.6	18	21	15	15.6	18	21	15	15.6	18	21	15	15.6	18	21
3	P	8	10	55	90	8	12	53	90	8	10	55	90	8	11	54	90
	λ	9	9.6	12	18	9	9.6	12	18	9	9.6	12	18	9	9.6	12	18
4	P	9	10	20	35	9	10	20	35	9	10	27	28	9	10	27	28
	λ	13.5	15	18	21	13.5	15	18	21	13.5	15	18	21	13.5	15	18	21
5	P	20	50	90	130	20	55	85	130	20	60	80	130	20	65	75	130
	λ	15	15.6	16.5	18	15	15.6	16.5	18	15	15.6	16.5	18	15	15.6	16.5	18

TABLE III
DEMAND BID AMOUNT (MW) AND BID PRICE DATA (€/MWH)

	HOUR 1					HOUR 2					HOUR 3					HOUR 4				
D	230	10	5	10	5	530	5	10	15	5	730	5	10	5	5	810	5	5	10	10
λ	36	24	18	12	6	36	24	21	15	6	36	24	18	15	6	36	24	18	12	6

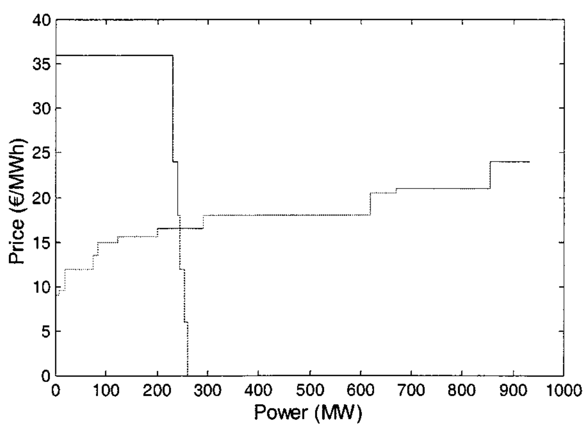

Fig. 3. Matching of generator and demand bids for the first hour.

TABLE IV
POWER OUTPUT OF THE UNITS (MW): BASE CASE

	UNIT 1	UNIT 2	UNIT 3	UNIT 4	UNIT 5
HOUR 1	0	40	73	19	113
HOUR 2	5.42	101.9	142.63	34.47	260.58
HOUR 3	77.96	149.02	163	55.03	290
HOUR 4	106.37	188.36	163	67.27	290

TABLE V
POWER OUTPUT OF THE UNITS (MW): SECOND CASE

	UNIT 1	UNIT 2	UNIT 3	UNIT 4	UNIT 5
HOUR 1	0	40	73	19	113
HOUR 2	6	108.52	123	36.13	271.35
HOUR 3	77.96	149.02	163	55.03	290
HOUR 4	106.37	188.36	163	67.27	290

2) Student groups (GENCOs) have half an hour to prepare their corresponding energy bids. Each group has available five units and each unit should bid four blocks of power and price. Therefore, each group should submit 20 energy blocks and their corresponding prices to the MO.
3) The instructor checks generator bids for consistency. If inconsistencies are found the corresponding group is eliminated from bidding and receives a penalty.
4) The instructor (MO) collects the bids electronically and applies the market clearing mechanism to determine market clearing prices and accepted and nonaccepted bids.
5) The instructor (MO) also computes the revenues and the profits of every group and broadcasts this information and the hourly market clearing prices to everyone. This information allows each group to know its ranking position with respect to its competitors and stimulates to bid efficaciously.

TABLE VI
POWER OUTPUT OF THE UNITS (MW): THIRD CASE

	UNIT 1	UNIT 2	UNIT 3	UNIT 4	UNIT 5
HOUR 1	0	40	73	19	113
HOUR 2	0	110.61	123	36.65	274.74
HOUR 3	77.96	149.02	163	55.03	290
HOUR 4	106.37	188.36	163	67.27	290

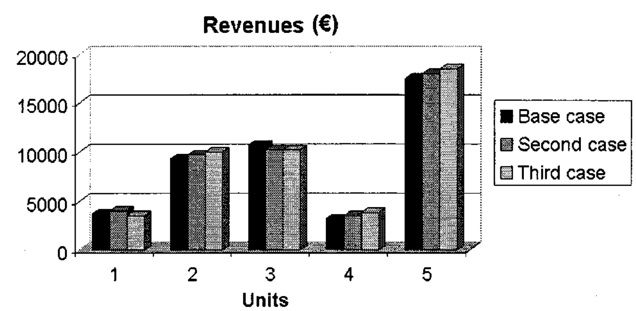

Fig. 4. Revenues for every unit in all case studies.

Steps 1 to 4 are repeated as many times as the time allocated to the lab allows. The first rounds are used for the students to get familiar with the functioning of the market and the last ones for ranking and grading them.

The students of the winning group (the group that has obtained the highest profit) receive a grade improvement in the final mark of the course.

V. Conclusion

This paper presents a lab experience to allow students in power engineering to get familiar with the practical functioning of a pool-based electricity market. This experience has clearly boosted student interest in power engineering subjects. Efficacious bidding requires the use of appropriate tools plus an important degree of technical intuition and experience regarding the behavior of the pool. Student creativity is promoted because they have to produce bids blending the results of the decision tools they have available with their technical intuition. In that sense, experience from previous bids and the use of a self-scheduling program greatly enhances students' ability to improve their bids. They also get exposed to the work in a competitive environment.

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