A Combinatorial Auction-Based Approach to Staff Shift Scheduling in Restaurant Business

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Abstract

This study focuses on improving the productivity of restaurant business. The productivity of restaurant business in Japan is lower than other service industries because the approach to improve the productivity has depended on experience and intuition by human workers in the service field. This study tries to adopt engineering/science approaches to staff shift scheduling in restaurant business; combinatorial auction is applied. Combinatorial auction-based staff scheduling is a negotiation-based approach between workers and a manager to reach an agreement in the multi-objective optimization problem; workers want to work as much as they can. On the other hand, the manager tries to reduce the number of workers if the service level can be kept with high enough to fulfil the customer's requirements. Resulting from the negotiation, the proposed method tries to find the staff shift schedule to realize maximization of service satisfaction composed by customer satisfaction, employee satisfaction and manager satisfaction. The effectiveness of the proposed method is discussed using the results of computer experiments using real data obtained from the Japanese cuisine restaurant.

Keywords

Restaurant business • Staff shift scheduling • Combinatorial auction

1 Introduction

This paper describes co-creation-based personnel shift planning method to maximize the service satisfaction consisting from not only customer satisfaction (CS) and employee satisfaction (ES) but management satisfaction (MS) intended for food industry in which the productivity is relatively low among service industries [1].

The personnel shift planning (staff scheduling) [2] is to create a shift schedule that considers the desired shift of each employee, taking into account the fairness of work among employees. The site manager is often performed by his/her own experiments and intuition; the manager needs large effort and long time to achieve feasible solutions. To support the managers creating the suitable staff shifts, scientific and/or engineering-based methods have been tried. Nurse scheduling [3, 4] to create a nurse work schedule in a hospital is a typical example. The nurse scheduling is one of combinatorial optimization problems and is often to be solved as a constraint satisfaction problem (CSP) because it is difficult to obtain feasible solutions [5] due to enormous search space and complicated constraints: nurse's ability, request for work time, affinity to other nurses and so on. However, nurse scheduling problem considers constraints while guaranteeing the quality of care and does not sufficiently consider the management perspective.

On the other hand, in the food service industry, seasonal, and even in daily hourly demand, fluctuation is large. It is

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needed to employ many non-permanent workers to adapt to the fluctuation and realize flexibility in the personnel shift. Because the food industry has also commercial purposes rather than public sector affairs content such as the hospital, management satisfaction (MS) also needs to be emphasized as well as customer satisfaction (CS) and employee satisfaction (ES). In addition, there is often a trade-off relationship among the satisfactions; it is important to consider the balance between indicators, rather than simply to improve one index. In this study, the staff scheduling has attempted modelling and seeking solutions as multi-objective problem. However, instead of obtaining the Pareto solutions (or portion thereof) using a mathematical planning approach modelled as multi-objective optimization problem, the approach to find a satisfactory solution to each other as a result of negotiations between the employees and management has been focused even keeping the quality of service. The framework of these negotiations in the actual food service industry is similar to the negotiation process of the auction protocol to repeat the bids and awards and finally to obtain feasible solutions. Combinatorial auction [6, 7] is applied to the staff shift scheduling in this study, and the basic effectiveness has been confirmed in the previous work [8]. The proposed method is applied to the real-scale problem, and the effectiveness of the proposed method is discussed by the results of computer experiments using the data from an actual Japanese cuisine restaurant.

2 Staff Shift Scheduling Using Combinatorial Auction

2.1 Outline of the Proposed Method

Japanese cuisine restaurant is chosen as the research target in this study. Because Japanese cuisine requires special technique for cooking, there is a distinction between staff roles, kitchen staff mainly corresponding for cooking. In turn, hall staff is responsible mainly for customer service. In this paper it is assumed that the target is only hall staff as the first stage of the research.

The shift schedule in the actual field of Japanese restaurants is planned as the following steps:

1. Each employee submits desired shift to the manager.
2. The manager determines the shifts by combining the desired shift submitted by each employee.
3. If each employee is not satisfied, adjustment is done by the manager, and the above steps are repeated until achieving the agreement of each employee.

Referring to the negotiation process with the manager and employees, a combinatorial auction that is one of the auction algorithms is adopted. In the combinatorial auction, the creation of each employee's desired shift in the above step 1 corresponds to the process of the bid determination problems. Shift decision in the above step 2 is equivalent to solving the winner determination problem of solving a combination of bids. When it is assumed that all possible combinations of work shifts are estimated, the solution of winner determination problem must be the optimal one. However, the search space is enormous and it is not a realistic problem to solve in the practical time. So the bid is set to a subset of all combinations, and repetition of bid and award processes is executed to obtain quasi-optimal solutions. This repetition corresponds to the process 3 in the above. Also in the actual restaurant, the employee chooses one possible shift from some candidates due to certain criteria; the employee sometimes compromises with the manager and other workers as the results of negotiations. An overview of these negotiation processes is shown in Fig. 1.

The entire algorithm of the proposed method using the combinatorial auction is depicted in Fig. 2. Auction bidders are each employee; the auctioneer is assumed to be the store manager. First, each bidder tries to explore the shift to maximize its own satisfaction (bid value maximization problem). Neighbourhood solutions of the obtained best solution are set to the bids in the initial iteration loop. In the next and following iterations, neighbourhood solutions of the solution awarded in the former iteration are set to the bids. In turn, a combination with highest satisfaction for the store manager is searched from a combination of the bids from all bidders (winner determination problem). With the use of combinatorial auction as described above, employees try to maximize employee satisfaction, and at the same time, the store manager is possible to solve the problem as maximizing management satisfaction; the structure of the multi-objective problem is decomposed along the auction structure. However, the bid creation process is carried out independently for each employee, so that not always feasible solution is obtained even with the bids of all employees. Therefore, by using Big-M method that can be considered as a kind of penalty method, the auction continues by selecting the least solutions in constraint violation if feasible solution cannot be obtained. In the following, each step is explained in more detail.

2.2 Nomenclature

$i = \{1, 2, \ldots, I\}$: The number of employee.
$d = \{1, 2, \ldots, D\}$: The number of planning period (day).
$t = \{1, 2, \ldots, T\}$: The number of planning period (time).
$n = \{1, 2, \ldots, N\}$: The number of times worked.
$p = \{1, 2, \ldots, P\}$: The number of work position.

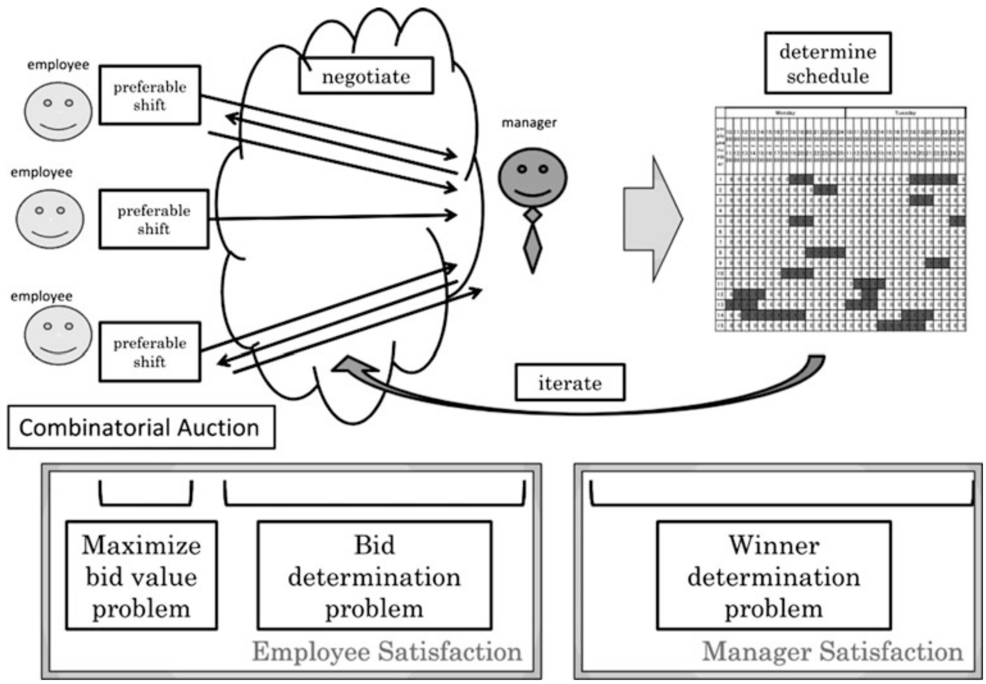

Fig. 1 Staff scheduling as negotiation process between the manager and employees

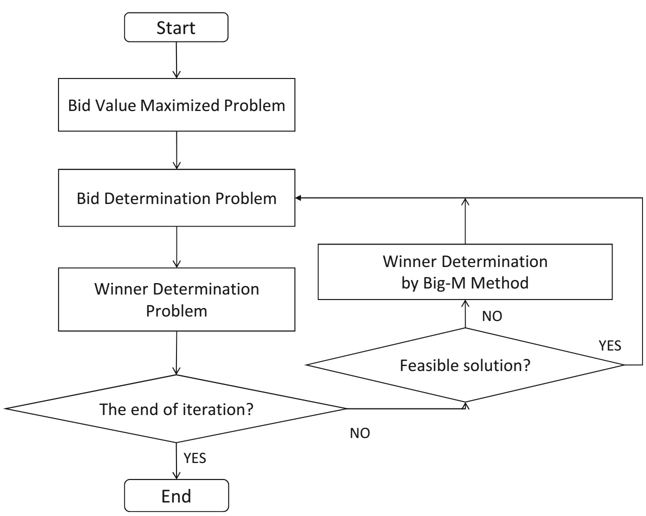

Fig. 2 Flow chart of the proposed auction-based method

$j = \{1, 2, \ldots, J\}$: The number of bids.
$c_{i,p}$: Ability of employee i working on p.
$c_i^{\max}$: Best ability of employee i.
$p_{i,j}$: Bid value of bid j of employee i.
$P_i^{\max}$: Best bid value of employee i.
$S_{i,d,t}$: Desired shift. If employee i can't work at time t on the day d, the value is set to 0. If employee i can work at time t, value is set to 1. If employee i can work at time t but he/she wouldn't like to work, then the value is set to -0.2.
$T_{\max}$: Upper limit of working hours in a day.
$T_{\min}$: Lower limit of working hours in a day, only if employee works on the day.
T_{rest}: Break time required to work up to the next.
$N_{d,t,p}$: Lower limit of ability at position p at time t on day d.
L_{week}: Upper limit of working hours in a week.
$st_{i,j,d}$: The start time of date d.
$ed_{i,j,d}$: The end time of date d.
α: Threshold.
$\tau_{i,j,d,t}$: Decision variable. If employee i works in the j-th bid at time t on day d, value is set to 1. Else if employee i does not work, the value is set to 0.
$\sigma_{i,j,d}$: Dependent decision variable. If employee i works in the j-th bid at day d, value is set to 1. Else if employee i does not work, the value is set to 0.
$x_{i,j}$: Decision variable in bid j of employee i, whether the bid is chosen or not.
w_i: Labour cost in 1 h of employee i.
y_n: Decision variable in Big-M method which means if the n-th constraint violation occurs, then the value is set to 1, otherwise 0.

2.3 Bid Value Maximization Problem

There are seven types of tasks that the hall staffs do: usher, reception, checkout, drink, banquet, catering and washing. It is assumed that each worker can perform all possible tasks within the same time. Each employee builds the desired work shift: the value 1 is set if the work is allowed in each

Table 1 An example of the desired shift

	10:00–11:00	11:00–12:00	12:00–13:00	13:00–14:00	14:00–15:00	15:00–16:00	16:00–17:00	17:00–18:00	18:00–19:00	19:00–20:00	20:00–21:00	21:00–22:00	22:00–23:00
Mon.	0	0	0	0	0	0	1	1	1	1	1	1	0
Tue.	0	0	0	0	0	0	1	1	1	1	1	1	0
Wed.	0	0	0	0	0	0	1	1	1	1	1	1	0
Thu.	0	0	0	0	0	0	1	1	1	1	1	1	0
Fri.	0	0	0	0	0	0	−0.2	−0.2	−0.2	−0.2	−0.2	−0.2	0
Sat.	−0.2	−0.2	−0.2	−0.2	−0.2	−0.2	1	1	1	1	1	1	0
Sun.	1	1	1	1	1	1	1	1	1	1	1	1	0

time zone; else if working cannot be allowed, 0 is set; and −0.2 is set if he/she does not want to work even possible. Table 1 represents the desired shift of an employee where the unit time of the shift is one hour, and the period of the plan is set to 1 week.

Based on the desired work shift, in order to create a bid maximizing the evaluation value for each employee, the problem is formulated as a {0, 1} binary integer programming problem. By solving this problem, it is possible to obtain a bid with the maximum employee satisfaction for each employee:

$$\text{maximize} \quad \sum_{d=1}^{D}\sum_{t=1}^{T}\tau_{i,j,d,t}S_{i,d,t} \quad (\forall i, j=1) \tag{1}$$

subject to

$$\begin{cases} L_{\min}^{\text{day}} \le \sum_{t=1}^{T}\tau_{i,j,d,t} \le L_{\max}^{\text{day}} & (\text{if}\,\sigma_{i,j,d}=1) \\ \sum_{t=1}^{T}\tau_{i,j,d,t}=0 & (\text{otherwise}) \end{cases} \quad (\forall i, \forall d, j=1) \tag{2}$$

$$st_{i,j,d+1} - ed_{i,jkd} + 24 \ge T_{\text{rest}} + 1 \quad (\text{if} \quad \sigma_{i,j,d+1}=1) \quad (\forall i,\, d=1,2,\ldots,D-1, j=1) \tag{3}$$

$$\sum_{d=1}^{D}\sum_{t=1}^{T}\tau_{i,j,d,t} \le L_{\max}^{\text{week}} \quad (\forall i, j=1) \tag{4}$$

$$\tau_{i,j,d,t}=0 \quad (\text{if}\ S_{i,d,t}=0) \quad (\forall i,\forall d,\forall t, j=1) \tag{5}$$

$$\sum_{d=1}^{d}\sigma_{i,j,d} \le LD_{\max}^{\text{week}} \quad (\forall t, j=1) \tag{6}$$

$$\begin{cases} \sigma_{i,j,d}=1 & \left(\text{if}\ \sum_{t=1}^{T}\tau_{i,j,d,t} \ge 1\right) \\ \sigma_{i,d,d}=0 & (\text{otherwise}) \end{cases} \quad (\forall i, \forall d, j=1) \tag{7}$$

$$\begin{cases} \tau_{i,j,d,t}=1 & (\text{if} \quad st_{i,j,d} \le t \le ed_{i,j,d}) \\ \tau_{i,j,d,t}=0 & (\text{otherwise}) \end{cases} \quad (\forall i, \forall d, j=1) \tag{8}$$

$$\begin{cases} 1 \le st_{i,j,d} \le T - L_{\min}^{\text{day}} + 1 & (\text{if} \quad \sigma_{i,j,d}=1) \\ st_{i,j,d}=0 & (\text{otherwise}) \end{cases} \quad (\forall i, \forall d, j=1) \tag{9}$$

$$\begin{cases} L_{\min}^{\text{day}} \leq ed_{i,j,d} \leq T & (\text{if} \quad \sigma_{i,j,d} = 1) \\ ed_{i,j,d} = 0 & (\text{otherwise}) \end{cases} \quad (\forall i, \forall d, j = 1) \tag{10}$$

$$\tau_{i,j,d,t}\sigma_{i,j,d}\{0,1\} \qquad (\forall i, \forall d, \forall t, j = 1) \tag{11}$$

The objective function is expressed as the Eq. (1). The decision variable in the bid value maximization problem is $\tau_{i,j,d,t}$; the value is set to 1 if employee i in j-th bid works in d-th day of time period t, otherwise 0. $S_{i,d,t}$ represents the desired shift; the value 1 means the employee i can work at day d and time t, "work possible". The value 0 represents the employee i cannot work, "work not permitted", and the value -0.2 means the situation in which employee can work but doesn't want to work, "work possible but does not want". The objective function represents how work shift of each employee meets much to the desired work shift; the objective function value becomes a larger value if the employee i works at the time zone of the "work possible". In turn, when employee i works at time zone "possible but does not want", the objective function value decreases.

The optimal solution obtained in this problem is included in the first bids, and the optimum value is also set as $P_i^{\max}$.

Constraints are expressed as the following: Eq. (2) represents the constraint on the upper and lower limits of the working hours of the day; Eq. (3) means the constraint by which each employee needs taking rest between former and latter works. Equation (4) represents the constraint on the upper limit in 1 week of working hours, Eq. (5) shows the decision variable is set to zero if the employee i cannot work at date d and time t and Eq. (6) represents the constraint on the maximal number of working days. Equation (7) defines the dependent variable $\sigma_{i,j,d}$, Eq. (8) represents the constraint on the start and end time of work and Eqs. (9) and (10) are the constraints on the dependent variables $st_{i,j,d}$ and $ed_{i,j,d}$.

2.4 Bid Determination Problem

In the bid determination problem, bids are created; at the initial step of iteration in the combinatorial auction, the bid with bid-number one is set as the combination of solutions of the bid value maximization problem of each worker. At the following steps of the iteration, the bid awarded in the previous iteration is set to the bid with bid-number one; elite strategy is adopted to prevent obtaining worse solutions than the previous iteration. Finally, the number of bids created as the neighbourhood is J-1.

How to create the neighbourhood solutions from the awarded solution is by first selecting a day from the shift with random manner, and then one algorithm is also applied randomly from the following nine algorithms. It is necessary to satisfy all constraints in the bid value maximization problem; the bid is discarded if the bid created does not satisfy the constraints, and the new bid is created again applying the neighbourhood creation algorithm.

1. One hour earlier the work start time.
2. One hour later the work start time.
3. One hour earlier the work end time.
4. One hour later the work end time.
5. One hour earlier the work start and end time for both.
6. One hour later the work start and end time for both.
7. Eliminate the work of the day.
8. Add a new work.
9. Eliminate work for the day, and choose randomly 1 day without work shift and add new works at that day.

In order to prevent that the bid value is much worse than the maximized employee satisfaction as the solution of bid maximization problem, the following additional constraint is provided:

$$p_{i,j} \geq \alpha P_i^{\max} \qquad (\forall i, \forall j) \tag{12}$$

where $P_{\text{i}}^{\max}$ represents the maximal bid value obtained by solving the bid value maximization problem and α is the threshold value with the range from 0 to 1. When the value of α is set to relatively high, the bid value also keeps relatively high value; employee satisfaction keeps high. In turn, management satisfaction can be high if the value of α is set to small value because the bid value can be small. The obtained solutions can be adjusted between employee satisfaction preferred solution and management satisfaction preferred solution according to the settings of the threshold value of α.

2.5 Winner Determination

In the winner determination problem, the combination of bids is determined from each worker's bids to minimize the objective function; a work shift of the entire store is built by choosing one work shift from alternative shifts of each worker. The objective function is set to minimize total labour input costs; management satisfaction is concerned in the winner determination problem. The winner determination problem is formulated from Eqs. (13), (14), (15), and (16):

$$\text{minimize} \qquad \sum_{d=1}^{d}\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J} x_{i,j}\tau_{i,j,d,t}w_i \tag{13}$$

subject to

$$\sum_{j=1}^{J} x_{i,j} = 1 \qquad (\forall i) \tag{14}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} x_{i,j}\tau_{i,j,d,t}c_{i,p} \geq N_{d,t,p}^{\min} \qquad (\forall d, \forall t, \forall p) \tag{15}$$

$$x_{i,j}\{0,1\} \qquad (\forall i, \forall j) \tag{16}$$

Decision variable in the winner determination problem is $x_{i,j}$. The value is set to one if the j-th bid of employee i is selected, otherwise the value is set to zero. The objective function calculates the total labour cost which multiplies the labour cost per unit time by the total working hours of each employee. Constraint represented in Eq. (14), in turn, only one bid per employee can be selected; the constraint represents only one proposal of work shift is awarded per one employee. Equation (15) represents the constraint on the necessary capability level; the constraint on the necessary capability value indicates the quality of adequate service provided by the employees, so that it can be maintained in the position p of d-th day of the time t. It is assumed that enough customer satisfaction is obtained by service provision from the employees. The winner is chosen in the winner determination problem, which is used to create neighbourhood solutions in the next bid determination problem.

2.6 Introducing Big-M Method

For bid for each employee to be created independently, not always feasible solution is obtained in the winner determination problem. Especially for the repetition of the early stages in combinatorial auction, small solution space consists only in the neighbourhood of the bid to be a satisfaction maximum of each employee or to be a winner in the former winner determination problem; there is a case in which it does not satisfy the constraints. In order to carry out the search process continuously even if feasible solution cannot be obtained in the winner determination problem, it is necessary to select a bid to be the winner. Therefore, the search space should be extended by relaxing some constraints, so that the feasible solution can be obtained.

This study employs the Big-M method that is a kind of penalty method to enable the derivation of feasible solutions as soon as possible during the repetitions of trials; the bid combination of less constraint violation is selected. The Big-M method by adding 0–1 variable that is a dummy variable relaxes constraints of the original problem and allows the inconsistencies in the original problem constraints. It is possible to specify infeasible part of the original problem by giving a value to the dummy variable.

Application of the Big-M method in the proposed method is realized by relaxation of the constraint Eq. (15) in the winner determination problem. The formulation is as follows:

$$\text{minimize} \qquad \sum_{n=1}^{N} y_n \tag{17}$$

subject to

$$\sum_{i=1}^{I} x_{i,j} = 1 \qquad (\forall i) \tag{18}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} x_{i,j}\tau_{i,j,d,t}c_{i,p} + My_n \geq N_{d,t,p}^{\min} \qquad (\forall d, \forall t, \forall p, \forall n) \tag{19}$$

$$x_{i,j}, y_n\{0,1\} \qquad (\forall i, \forall j, \forall n) \tag{20}$$

Decision variables in the problem are $x_{i,j}$ and y_n; if the j-th bid of employee i is chosen, the value is set to one, and zero otherwise. When constraint Eq. (15) is violated, y_n is set to one, otherwise zero. The objective function is minimization of the sum of decision variables y_n, which means to minimize the number of violations of constraints Eq. (15). Another constraint Eq. (18) means one bid per each employee can only be selected, and constraint Eq. (19) represents constraint Eq. (15) has been relaxed by the Big-M method. Constant M is set to relatively big value as the penalty for constraint violation.

By performing the winner determination problem using the Big-M method, it is possible to select a winner work shift if the capability of employee in a working time zone is less than the minimal value. It can be also expected that feasible solutions can be reached soon so that the number of constraint violation is kept to be small. Furthermore, by examining the y_n, it is possible to determine the time zone and the day when the capacity is insufficient in which working position; the manager can negotiate with employees and modify relatively easily the work shift.

3 Computer Experiments

3.1 Experimental Settings

Hall staff in the Japanese cuisine restaurant is selected as the target, and computer experiments are conducted. The following data is obtained from the real restaurant:

Table 2 Experimental setting

Number of employee	22
Regular employee	3
Non-regular employee	19
Planning term (days)	7
Planning term in a day (hours)	13
Number of bid	50
Upper limit of work (hours/day)	12
Lower limit of work (hours/day)	2
Break time to next work (hours)	12
Weekly upper limit of work (hours/week)	60
Weekly upper limit of work (days/week)	5
Number of work positions	7

– Desired work shift of each worker
– Determined shift built by the manager
– Required number of people in each position p necessary capability value
– Labour cost of each worker

The hall staff has 22 people in the targeted store; three of them are full-time workers, and the rest of the 19 people are non-regular employees. Regular employees are required to work at least 40 h in 1 week and are modelled as employees with such constraint. Experimental conditions for more in detail are shown in Table 2. Each from the top in the table follows the number of employee, the number of full-time employees, non-regular employees, planning period (day), planning period (time) in 1 day, the number of bid, the upper/lower limits for working hours in a day, minimum break time for the next work, upper/lower limits in a week, and business position number (guide, service, cash register, drink, banquet orders, catering, the washing place). In the experiments, the threshold value α in the bid determination problem is varied from 0.0 to 1.0 in increments of 0.1, and the relationships between the ES and MS are discussed.

3.2 Results and Discussion

Experimental results are shown in Table 3. Max ES in the table is the sum of the evaluation values of bids obtained in the bid value maximization problem. ES means the sum of the evaluation values of bids of final winners, and MS indicates the value of the winner determination problem (yen). Also, time units in the calculation time required for combinatorial auction are second. The resulting value is the average of all 10 trials.

It is confirmed that ES decreases and MS increases as the threshold decreases; in turn, ES increases and MS decreases as the threshold value increases. When the value of the threshold is large, the desire of employee can come true because neighbourhood solutions are created only in the neighbourhood of the best solution at the bid value maximization problem (the value of the MaxEX). On the other hand, because the value of the threshold value is small, the value of ES is small as compared with the values of MaxEX; it becomes compromised solution for employees. Labour costs are reduced conversely and the management satisfies. From the above results, it is confirmed that there is trade-off relationship between ES and MS.

Table 3 Experimental results

α	Max ES	ES	MS	Time
0	659	306.2	411041	49.08
0.1	659	306.2	413235	48.73
0.2	659	312.5	418507	49.68
0.3	659	324.2	427758	46.6
0.4	659	347.4	450076	48.12
0.5	659	382.3	479238	49.52
0.6	659	420.5	512247	46.65
0.7	659	476	572314	45.84
0.8	659	543	652852	45.34
0.9	659	608	731390	45.77

If the actual shift in the targeted restaurant is evaluated in the same one week of labour costs to the original, it is about ¥ 618,000, and to correspond with the experimental results, threshold corresponds to between 0.7 and 0.8.

This shift in the actual restaurant can be considered to indicate that it is a shift in consideration of the desire of employees.

These results suggest the efforts to further improve labour productivity although employee capacity values are divided into simple three levels in this study and it is not considered to model all the differences between the proposed model and the actual capacity of employee representation.

In the viewpoint of calculation time, each experiment also finishes in about 50 s; it is possible to derive the solution in the short time. It is revealed that the proposed method is possible to support the manager by using a computer support to create a shift deriving over several hours in the actual restaurant.

4 Concluding Remarks

In this paper, the negotiation process is focused between the employees and the store manager in the personnel shift planning of a real shop, so that a method was proposed to develop a personnel shift plan by applying the framework of combinatorial auction. Computer experiments were performed to verify the proposed method by using the data of the actual Japanese cuisine restaurant, and it was confirmed that the proposed method could handle a trade-off relationship between employee satisfaction and management satisfaction. Also, by comparing the labour costs in the actual store, it was suggested that there was a potential for further efficiency.

Customer satisfaction is currently introduced as a constraint condition; it is modelled as any solutions can obtain sufficient customer satisfaction. In the future work, the customer satisfaction should be also modelled in the objective function; co-creative design method of staff shift scheduling will be realized, in which customer, employee and manager can be satisfied.

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