# A Systematic Approach to Combinatorial Auction Design

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## Abstract

As the interest in the combinatorial auction has increased, diverse combinatorial auction market types have been proposed. Although there have been several studies on the combinatorial auction design, the studies covered some factors or partial dimensions of combinatorial auction design. Given the potential practical value of combinatorial auctions, it is necessary to approach it with an integrated and systematic design methodology for supporting a comprehensive range of combinatorial auction models. Thus, we present a systematic framework for combinatorial auction design methodology. In particular, we classified the combinatorial auction architecture types, process types, and mechanism types. This framework characterizes the different combinatorial auction models, and lead to a useful taxonomy of the combinatorial auction design factors and taxonomy of the market types by coordination among the design factors. In addition, we illustrate an n-bilateral combinatorial auction market, derived from our design methodology, to show the viability of our study.

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## Abstract

As the interest in the combinatorial auction has increased, diverse combinatorial auction market types have been proposed. Although there have been several studies on the combinatorial auction design, the studies covered some factors or partial dimensions of combinatorial auction design. Given the potential practical value of combinatorial auctions, it is necessary to approach it with an integrated and systematic design methodology for supporting a comprehensive range of combinatorial auction models. Thus, we present a systematic framework for combinatorial auction design methodology. In particular, we classified the combinatorial auction architecture types, process types, and mechanism types. This framework characterizes the different combinatorial auction models, and lead to a useful taxonomy of the combinatorial auction design factors and taxonomy of the market types by coordination among the design factors. In addition, we illustrate an n-bilateral combinatorial auction market, derived from our design methodology, to show the viability of our study.

**Keywords:**

combinatorial auction; combinatorial auction design methodology; n-bilateral combinatorial auction

## Introduction

Combinatorial auctions are preferable since they enable bidders to bid on combinations of items as opposed to only on single item. In a traditional auction format where the items are auctioned separately, to decide what to bid on an item, a bidder needs to estimate which other items he/she will receive in the other auctions, requiring an intractable look ahead in a series of auctions. Even after looking ahead, residual uncertainty exists due to incomplete information about the other people's bids. Therefore, the need for new auction mechanisms has increased. Combinatorial auctions can be used to overcome these deficiencies that stem from the problems of uncertainties [1, 17, 25, 33, 36]. Combinatorial auctions (also called as multi-item auctions or bundle auctions) refer to auctions for multiple items at the same time, as opposed to single item auctions. Compared to single item auction types, they keep bidders from the risk of receiving only parts of combinations that would be valuable to the bidders. By giving more expressive power to bidders through complementary or substitute bids, the combinatorial auction has received much attention.

Most of the combinatorial auctions proposed in the literature are one-sided supply chain mechanisms: either multiple buyers compete for items sold by one seller or multiple sellers compete for the right to sell to one buyer. Either way, there is a possibility that the monopoly side has the advantage of commanding a greater portion of the market surplus. By contrast, there are some studies on combinatorial exchange in which multiple buyers and sellers exist [4, 5, 12, 13, 33, 37]. The combinatorial exchange usually refers to a market for financial items such as stocks or bonds. The participants submit bids to buy or sell bundles of those items. The objective of the auction is to maximize the total market surplus [37].

As mentioned above, the combinatorial auction has taken diverse mechanisms to satisfy the market needs. Each combinatorial auction type has a different architecture, trading rules and process, and trading strategies by participants. This requires a comprehensive and systematic approach to analyze and design combinatorial auction markets. Although there have been several studies covering some factors or partial dimensions of combinatorial auction design, it is quite important to approach it with an integrated and systematic design methodology for supporting a comprehensive range of combinatorial auction models and identifying correlation between design factors. Thus, in this study, we propose an integrated and systematic framework for combinatorial auction design methodology. It is based on three phases - architecture design, protocol design, and trading strategy design. We classified the combinatorial auction architecture types, process types, and mechanism types, and proposed the seller's and buyer's decision models that reflect their trading strategies in the auction process. Finally, an illustration of n-bilateral combinatorial auction, derived from our design methodology is briefly described.

This framework characterizes the different combinatorial auction models, and lead to a useful taxonomy of the combinatorial auction design factors and taxonomy of the market types by coordination among the design factors. The proposed design methodology plays an important role as a guide or tool for analyzing or designing a specific auction market in the real world.

## A Review of Related Research

During the past few years, combinatorial auctions have received much attention in the literature [16, 20, 29, 30]. There have been studies on operation research focused on optimization models [3, 25, 29], efficient algorithms for winner determination [22, 24, 31], and economics based research mainly on the proof of the existence of equilibrium status and economic efficiency [21, 35]. As combinatorial auction mechanisms have diversified, several studies have covered combinatorial auction design issues.

The design of new market mechanisms is a new and emerging field [7]. Market type design creates a meeting place for buyers and sellers, and a format for transactions [8]. Electronic market design is a challenging task and involves interdisciplinary characteristics.

There have been several studies on combinatorial auction designs, and they are listed in Table 1.

Bichler et al. [7] suggested several design factors for resource allocation problems on the combinatorial auction market. In this research, the primary criteria for characterizing the allocation problems are the number of participants, and the types of traded goods.

Abrache et al. [2] discussed several design issues that are encountered in the design of combinatorial auctions. These issues are related to the formulation of the winner determination problem, the expression of combined bids, and the design of progressive combinatorial auctions.

Pekec and Rothkopf [26] described the single-round, first-price sealed bidding, Vickrey-Clarke-Groves (VCG) mechanisms, uniform and market-clearing price auctions, and iterative combinatorial auctions as standard combinatorial auction types. In a similar study, Sandholm et al. [34] proposes a wider range of combinatorial market designs: combinatorial auctions, combinatorial reverse auctions, and combinatorial exchanges, with one or multiple units of each item, with and without free disposal.

Porter et al. [27] described several combinatorial auction designs such as continuous auctions, multi-round auctions, and hybrid auctions that combine continuous bidding and multi-round auctions.

On the other hand, the studies on optimized allocation reflecting the strategies of seller or buyer have been proposed. The optimal allocation problem in combinatorial auctions is commonly formalized as an integer programming problem [37]. Given a set of bids on subsets of the items in a combinatorial auction, the goal of the auctioneer is to assign items to the bidders such that the auction objective is maximized or minimized according to the characteristic of the objective. In case of optimization problems underlying the combinatorial auction, several studies present the constraint factors that impact the optimization model formulation.

In case of Bichler et al. [6], they proposed the allocation constraints such as the maximum or minimum number of winning sellers, and the maximum or minimum amount procured from each seller for the reverse combinatorial auction. In addition, Giovannucci et al. [14] suggested the constraint factors such as the maximum or minimum number of winning sellers, supply capacity, maximum or minimum supply volume, maximum or minimum demand volume, and reserve price.

Abrache et al. [1] proposed the bidding operator, which is a two-level representation of a combined bid. At the inner level, bidding operators impose conditions on the executed proportions of packages of atomic single-item bids. The inner-level bidding operators include the composition operators such as the proportion ordering operator, the equal operator, the SIMPLEX operator, the selection operators such as the maximum or minimum number of atomic bids, and the hybrid operators that combine functions of the selection operator and composition operators. In contrast, the outer-level bidding operators include logical operators AND, OR, and XOR.

Similarly, Nisan [24] introduced several logical bidding operators for combinatorial auction: OR bids, XOR bids, OR-of-XOR bids, and so on.

Although, several studies have emphasized the design problem of the combinatorial auction market and covered a few design factors or partial dimensions of combinatorial auction design, these only analyzed parts of the characteristics that compose combinatorial auction markets. The overall analysis requires comprehensive and systematic approaches for designing the combinatorial auction markets.

## Combinatorial Auction Design Model

In combinatorial auction markets, buyers and sellers meet as auctioneers or bidders in the markets. They announce call-for-bids (CFPs), submit combinatorial bids, select partners by their trading strategies while observing the auction rules. In general, the market should be designed with the following features when we review the market design-related literature [7, 8, 19].

1. Who meets, where they meet, and what is their relationship with each other?
2. Which processes and rules do they trade with?
3. What are their trading strategies in the process?

The first feature addresses the architecture for the marketplace, the second addresses trading protocol for trading processes and rules, and the third addresses trading strategy of each participant in the market. This leads to a combinatorial auction market design with a three-phased approach: architecture, protocol, and trading strategy designs. Figure 1 depicts the combinatorial auction design model based on these three phases. Combinatorial auction market requirements are actualized as a specific combinatorial auction market through architecture design, protocol design, and trading strategy design successively.

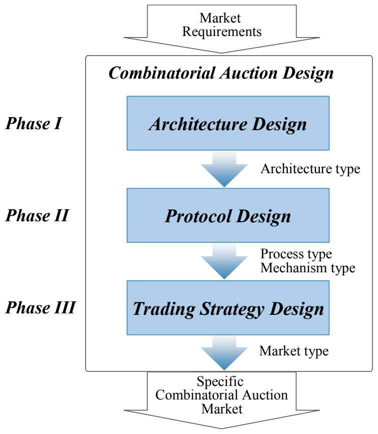


Figure 1 – Combinatorial Auction Design Model

## Combinatorial Auction Design

### Architecture Design

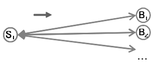
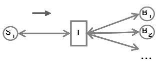
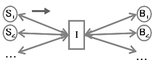
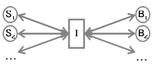
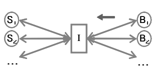
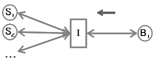
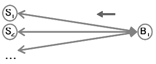
In the architecture design phase, the overall market structure including market and participants is defined. The factors that determine the market structure are the market place, cardinality of participants, and relationship between participants.

The market place defines an e-marketplace where the real transaction among participants is formed. There are the seller's, intermediary's, and buyer's e-Marketplaces. The seller's e-Marketplace is the most common B2B marketplace. Most of the manufacturer-driven or retailer-driven e-marketplaces belong to this category. The intermediary's e-Marketplace is usually operated by an auction agency, which runs the marketplace where buyers and sellers participate for trading. The buyer's e-Marketplace using the auction mechanism is generally the reverse auction market.

The cardinality of participants means the numeric relationship between sellers and buyers. The sellers and buyers meet in the marketplace with three types of cardinality: 1-n, m-1, and m-n. In the seller's e-Marketplace, in general, one seller is available as a participant. In a buyer's e-Marketplace, on the contrary, one buyer is available. But, in case of the intermediary's e-Marketplace, one or more sellers and buyers can participate in the auction process.

The relationship between participants is determined by the role of each market participant. There are three alternatives for the relationship between participants: auctioneer-bidder, auctioneer-coordinator-bidder, and bidder-auctioneer-bidder. The auctioneer- bidder relationship means the general or reverse combinatorial auction operated in the seller's or buyer's e-Marketplace. The auctioneer-coordinator-bidder means the general or reverse combinatorial auction in the intermediary's e-Marketplace. The intermediary plays the role of coordinator. The bidder-auctioneer-bidder relationship means the combinatorial exchange in which sellers and buyers participate as bidders at the same time in the intermediary's e-Marketplace. The intermediary plays the role of auctioneer. The combinations of alternatives of the three factors make seven significant architecture types as presented in Table 1.

Table 1 - Combinatorial Auction Architecture Types

| Type | Market place | Cardinality of participant | Relationship b/t participant | Structure |
|---|---|---|---|---|
| I | Seller's e-Marketplace | 1 Seller - n Buyers | Auctioneer-Bidder |  |
| II | Intermediary's e-Marketplace | 1 Seller - n Buyers | Auctioneer-Coordinator-Bidder |  |
| III | | m Sellers - n Buyers | Auctioneer-Coordinator-Bidder |  |
| IV | | | Bidder-Auctioneer-Bidder |  |
| V | | | Bidder-Coordinator-Auctioneer |  |
| VI | | m Sellers - 1 Buyer | Bidder-Coordinator-Auctioneer |  |
| VII | Buyer's e-Marketplace | m Sellers - 1 Buyer | Bidder-Auctioneer |  |

The symbols S, I, and B mean seller, intermediary, and buyer respectively.

Architecture I is a general combinatorial auction market operated in the seller's e-Marketplace. In this architecture, the buyers (bidders) visit the seller's e-Marketplace. Based on the submitted bids by buyers, each seller (auctioneer) selects optimal bids. The cases of FCC spectrum allocation [23] or airport landing slot allocation [28] are included in this architecture type. Architecture II is basically the same as the architecture I, but the main difference is that the intermediary provides the auction service. The buyers visit the intermediary's e-Marketplace and submit bids in the auction market opened by one seller. The sales problem of TV advertising airtime [18] can be classified into architecture type II. Architecture III, IV, and V are the marketplaces in which multi-buyers and multi-sellers participate. Architecture III is a general n-bilateral combinatorial auction, which is a newly proposed market type in our research. In the general n-bilateral combinatorial auction, operated by the intermediary, multi-sellers participate as auctioneers and multi-buyers as bidders. Architecture IV is a typical combinatorial exchange [12, 32, 34] where a combinatorial double auction is done by matching sellers and buyers so as to maximize market surplus. Multi-sellers and multi-buyers participate in the combinatorial exchange as exchange traders. That is, they are allowed to both buy and sell items simultaneously, or just to buy, or just to sell [34]. Architecture V, also newly proposed in our study, is buyers' driven reverse n-bilateral combinatorial auction, in which multi-buyers participate as auctioneers and multi-sellers as bidders. In architecture III and V, the intermediary plays a coordinator role. Architecture VI is a reverse combinatorial auction opened in the intermediary's e-Marketplace. Transportation procurement [15] and commodities procurement [31] are examples of real cases. Finally, architecture VII is a typical reverse combinatorial auction in the buyer's e-Marketplace. Government procurement [10] or transportation service procurement [16] are classified into this architecture type.

## Protocol Design

In the protocol design phase, the rules for bidding, bidder selection, and stopping are defined as presented in Table 2. The protocol design factors are specified by the auctioneer. The bidding rule refers to the rules that bidders follow in the auction process. They include the number of units per item, bidding type, round type, upper limit of bidding rounds per bidder, upper limit of total bids per bidder, and upper limit of bids in each round per bidder. In combinatorial auctions, the number of item type is basically multiple. Thus the number of units per item is classified into single or multiple units. The bidder selection rule is the policy on the selection of bidders. This includes bidder selection unit and pricing scheme. The bidder selection unit concerns the timing of bidder selection. The alternatives of bidder selection unit are round or bid. Thus, bid selection is occurred at the end of each round or whenever a new bid is entered. Finally, the stopping rule refers to the rule on the termination of the auction process. For the market closing condition factor, there are four alternatives; no new bids from any bidders, predetermined number of rounds, predetermined objective, and predetermined market surplus. The predetermined objective can be applied to the general or reverse combinatorial auction because it can be applied to the case that there is only one seller or buyer. The predetermined market surplus can be applied to the combinatorial exchange.

Table 2 - Factors for Combinatorial Auction Protocol Design

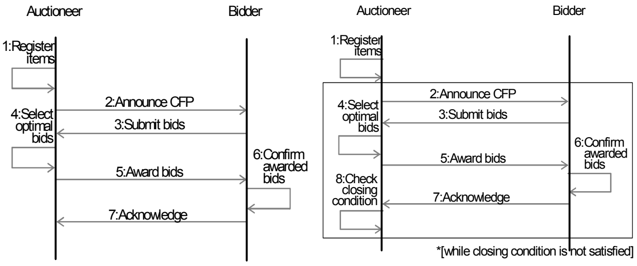
| Classification | Factors | Alternatives |
|---|---|---|
| Bidding Rule | Number of units per item | Single unit |
| | | Multiple unit |
| | Bidding type | Simultaneous |
| | | Continuous open cry |
| | | Continuous sealed bid |
| | Round type | Single round |
| | | Multiple round |
| | Upper limit of bidding rounds per bidder | Number of rounds |
| | Upper limit of total bids per bidder | Number of bids |
| | Upper limit of bids in each round per bidder | Number of bids |
| Bidder selection rule | Bidder selection unit | Round |
| | | Bid |
| Stopping rule | Closing condition | No new bids |
| | | Predetermined number of rounds |
| | | Predetermined objective |
| | | Predetermined market surplus |

Basic process types are defined by the factors that directly affect the process classification among the protocol design factors. The factors that determine process types are bidding type, round type, and bidder selection unit. Five basic process types are presented in Table 3.

Table 3 - Combinatorial Auction Process Types

| Type | Process classification factors | | |
|---|---|---|---|
| | Bidding type | Round type | Bidder selection unit |
| I | Simultaneous | One round | Round |
| II | | Multiple rounds | Round |
| III | Continuous | One round | Round |
| IV | | | Bid |
| V | | Multiple rounds | Round |

An illustration of each basic process type is depicted in Figure 2. Process type I is the simultaneous auction in only one round. Optimal bids are selected at the end of the round. which is batch selection. Process type II is the same as process type I over multiple rounds, namely it is an iterative auction process.

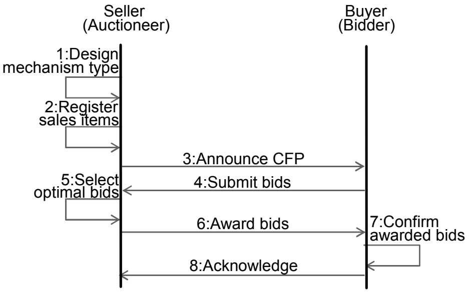


(a) Process I (b) Process II

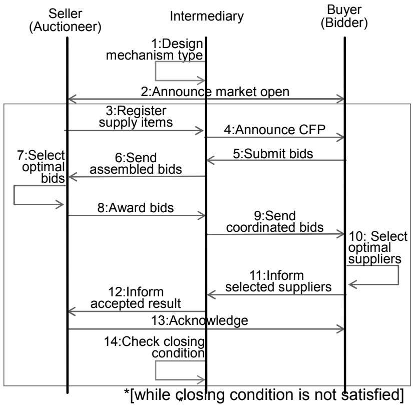
Figure 2 - Combinatorial Auction Process Types

Specific combinatorial auction mechanism types are defined by the combination of the architecture types and the combinatorial auction process types. We classify 35 combinatorial action mechanism types by the combination of seven architecture types and five basic process types, also illustrated some mechanism types in Figure 3.

Figure 3(a) is the general combinatorial auction in the seller's e-Marketplace defined by the combination of architecture type I and process type I. Figure 3(b) is the general n-bilateral combinatorial auction in the intermediary's e-Marketplace, the combination of architecture type III and process type II.



(a) General Combinatorial Auction with Simultaneous One Round



(b) General N-Bilateral Combinatorial Auction with Simultaneous Multiple Rounds

Figure 3 - Illustration of Mechanism Types

## Trading Strategy Design

### *Bidding Strategies*

In the trading strategy design phase, the bidding, bidder selection, and auctioneer selection strategies are defined. As the first process for the combinatorial auction, when the call-for-bids are announced in the bidding stage, the bidders specify the bidding strategy. The bidding strategy is to define the bid requirements on bid items. The bid requirements, based on endogenous bidding strategy, are composed of bids on items, quantity, and unit bid price, and bid selection requirements.

Bid selection requirements can be expressed using bid selection operators: ***AND***, ***OR***, ***XOR***, ***PRIORITY***, and ***IF-THEN*** etc. Eq. (1) ~ (4) depicts bid requirements from a bidder. $\beta$, $\beta_1$, and $\beta_2$ means subsets of bids.

*Bid Requirements* = ({*Bid*}, {*Bid Selection Requirements*}), (1)
where *Bid* = (item, quantity, unit bid price), (2)
*Bid Selection Requirements* =
Bid Selection Operator ($\beta$) or (3)
Bid Selection Operator ($\beta_1$, $\beta_2$) (4)

All bids without bid selection requirements are basically interpreted as ***OR*** condition and bidders can add bid selection requirements such as Eq. (3) or Eq. (4) according to their strategies. ***AND***, ***XOR***, and ***PRIORITY*** operators obey Eq. (3) and ***IF-THEN*** obeys Eq. (4). ***AND*** means all bids in a bid set should be executed. ***OR*** means at least one bid in a bid set should be executed. ***XOR*** means just one bid in a bid set should be executed. ***PRIORITY*** means the ordering of the executed bids, namely, the first proposed bid should be accepted before the next proposed bids are accepted. ***IF-THEN*** means one subset of a bid set should be executed when the other subset of a bid set is executed.

### *Bidder Selection Strategies*

Each auctioneer sets up the bidder selection strategy as the second process. The bidder selection strategy is to obtain the best bids from the bidders.

The *Bidder Selection Strategy* is composed of endogenous and exogenous strategies as presented in Table 4. The endogenous strategy is composed of a goal and constraints sets. The goal is dependent on the auctioneer's objective. Therefore we call it an *Endogenous Goal*. The possible goals of the auctioneers may be the maximization of sales, profit, or market surplus. The maximization of sales can be applied when one or more sellers are auctioneers. Profit maximization can be applied when one or more buyers are auctioneers. The maximization of market surplus is generally applied with a combinatorial exchange.

The constraints are classified into two categories. One is exogenous constraints by the auctioneer's trading strategies and the other is exogenous constraints by the bid selection requirements from the bidders. The former is the *Endogenous Strategies* and the latter *Exogenous Strategies*.

The allocation, price, and resource constraints are endogenous constraints derived from endogenous strategies. The bid selection constraints, derived from bid selection requirements by each bidder, affect the bidder selection model as exogenous strategy.

Table 4 - Factors for Bidder Selection

| Factors | | Alternatives |
|---|---|---|
| Endogenous strategy | Goal | Max total sales |
| | | Max total profit |
| | | Max market surplus |
| | Allocation constrains | Maximum number of winning buyers |
| | | Maximum number of winning buyers |
| | | Maximum number of accepted bids |
| | | Minimum number of accepted bids |
| | | Maximum allocation volume per buyer |
| | | Minimum allocation volume per buyer |
| | Price constraints | Accepted minimum unit price |
| | Resource constraints | Supply capacity limit |
| | | Total qty bought less than total qty sold |
| Exogenous strategy | Bid selection constraints | AND (***β***) |
| | | OR (***β***) |
| | | XOR(***β***) |
| | | PRIORITY (***β***) |
| | | IF-THEN (***β1***, ***β2***) |

The *Bidder Selection Model* has a goal and one or more constraints as depicted in the semantic representation in Eq. (5).

*Bidder Selection Model* = (*Model_Goal*{$G_i$};

$$\mathit{Model\_Constraints}\{C_j, D_k\}) \qquad (5)$$

The model is identified by *Model Identification Rules* as below.

IF *Endogenous_Strategy*($G_i$) THEN *Model_Goal*($G_i$),
IF *Endogenous_Strategy*($C_j$) THEN *Model_Constraints*($C_j$),
IF *Exogenous_Strategy*(*Bid_Selection_Requirements*($d_k$)
THEN *Model_Constraint*($D_k$).

***Auctioneer Selection Strategies***

The third process in the combinatorial auction is to select the optimal auctioneers. The optimal auctioneer selection process occurs only in the general or reverse n-bilateral combinatorial auction market in which multi-auctioneers and multi-bidders participate. The auctioneer selection strategy of the bidders refers to the strategy of acknowledging optimal bids among the bids awarded by the auctioneers. The *Auctioneer Selection Model* is composed of a goal and constraints sets. The goal and constraints are all endogenous for bidders. The bidder's goal is to select the optimal bids among awarded bids to maximize bidding objective value. Like the bidder selection strategy, the auctioneer selection strategy is affected by the cardinality of participants, in that each bidder should select optimal auctioneers among candidates when there are several auctioneers. The possible goal for buyers is minimization of total purchase price. There are several constraints related to allocation, cost, and bid selection as shown in Table 5. The auctioneer selection model has basically the same form as the bidder selection model.

Table 5 - Factors for Auctioneer Selection

| Factors | | Alternatives |
|---|---|---|
| Endogenous strategy | Goal | Min total purchase price |
| | Allocation constraints | Maximum number of winning sellers |
| | | Maximum number of winning sellers |
| | | Maximum number of accepted bids |
| | | Minimum number of accepted bids |
| | | Maximum allocation volume per seller |
| | | Minimum allocation volume per seller |
| | Cost constraints | Maximum unit item price |
| | | Budget limit |
| | Bid selection constraints | AND ($\boldsymbol{\beta}$) |
| | | OR ($\boldsymbol{\beta}$) |
| | | XOR($\boldsymbol{\beta}$) |
| | | PRIORITY ($\boldsymbol{\beta}$) |
| | | IF-THEN ($\boldsymbol{\beta 1}, \boldsymbol{\beta 2}$) |

## Illustration of N-Bilateral Combinatorial Auction Market Design

In this section, we show the viability of our design methodology with an illustration for the general n-bilateral combinatorial auction market composed of multi-auctioneers, multi bidders, and an intermediary. The alternative values for the architecture and protocol design factors are depicted in Table 6.

In the architecture design phase, the intermediary opens general n-bilateral combinatorial auction market, where multi-sellers and multi-buyers meet as auctioneers and bidders respectively. This situation corresponds to architecture type III. In the protocol design phase, the intermediary specifies the bidding, bidder selection, and stopping rules. We assume that multiple units, simultaneous bidding, and multiple rounds for the factor number or units per item, bidding type, and round type respectively. Upper limit of bidding rounds per bidder, total bids per bidder, and bids in each round per bidder are all unlimited. The intermediary also defines the bidder selection unit as a round. Thus, the auction process follows process type II – simultaneous multiple rounds – in protocol design. Next the intermediary defines the closing condition as the predetermined number of rounds. Thus, in this case, the mechanism type is the general n-bilateral combinatorial auction with simultaneous multiple rounds.

Table 6 - Illustration of Architecture and Protocol Design

| Phase | Factor | | Value |
|---|---|---|---|
| Architecture design | Market place | | Intermediary's e-Marketplace |
| | Cardinality | | m Sellers-<br>n Buyers |
| | Relationship | | Auctioneer-Coordinator-Bidder |
| Protocol design | Bidding rule | Number of units per item | Multiple units |
| | | Bidding type | Simultaneous |
| | | Round type | Multiple rounds |
| | | Upper limit of bidding rounds per bidder | Unlimited |
| | | Upper limit of total bids per bidder | Unlimited |
| | | Upper limit of bids in each round per bidder | Unlimited |
| | Bidder selection rule | Bidder selection unit | Round |
| | Stopping rule | Closing condition | Predetermined number of rounds |

After the upper two phases are specified by the intermediary, the design information is delivered to the sellers or buyers. Then the sellers and buyers decide their trading strategies. In this section, we describe only the bid requirements and bidder selection model since the auctioneer selection model is similar to the bidder selection model. We assume that the bidders request only *XOR* as bid selection requirements. This affects the bid selection constraints of bidders. The auctioneer sets up the bidder selection strategy. He/she has a goal to maximize total sales and constraints of maximum number of winning sellers, minimum allocation volume per buyer, reserve unit price, and supply capacity. In addition, the bid selection constraint of *XOR*{*Bid*} comes from the bid selection requirements from bidders.

Trading strategy design leads the following bidder selection model in the semantic representation according to Eq. (6)

*Bidder Selection Model* =
(*Model_Goal*{Max total sales};
*Model_Constraints*{maximum number of winning buyers,
minimum allocation volume,
supply capacity,
reserve unit price,
***XOR***{*Bid*}}). (6)

The optimization model can be used to solve the semantic bidder selection model. The following mathematical expressions mean the Integer Programming for the identified bidder selection model Eq. (6).

$$\max \sum_{i=1}^{l} \sum_{j=1}^{m[i]} \sum_{k=1}^{n} Q_{ijk}\, U_{ijk} X_{ij}\,, \tag{7}$$

s.t.

$$\text{if} \sum_{j=1}^{m[i]} Q_{ijk} X_{ij} \geq 0, \text{ then } Y_{ik} = 1, \text{ else } Y_{ik} = 0 \text{ for all } i,\ k, \tag{8}$$

$$\sum_{i=1}^{l} Y_{ik} \leq N_{max,k} \quad \text{for all } k, \tag{9}$$

$$\sum_{j=1}^{m[i]} Q_{ijk}\, X_{ij} \;\geq\; D_{min,k} \quad \text{for all } i,\ k, \tag{10}$$

$$\sum_{j=1}^{m[i]} \sum_{i=1}^{v} Q_{ijk} X_{ij} \;\leq\; C_k \quad \text{for all } k, \tag{11}$$

$$\text{if } Q_{ijk} X_{ij} > 0 \text{ then } U_{ijk} X_{ij} > R_k \quad \text{for all } i, j, k, \tag{12}$$

$$\sum_{j=1}^{m[i]} X_{ij} \;\leq\; 1 \quad \text{for all } i, \tag{13}$$

$$X_{ij} \in \{0,1\} \quad \text{for all } i, j, \tag{14}$$

$$Y_{ij} \in \{0,1\} \quad \text{for all } i, j. \tag{15}$$

where $X_{ij}$ is 1 if bid $j$ is allocated to buyer $i$ and 0 otherwise, $Y_{ik}$ is 1 if item $k$ is sold to buyer $i$ and 0 otherwise, $Q_{ijk}$ is the bid item quantity for item $k$ in bid $j$ of buyer $I$, $U_{ijk}$ is the bid unit price for item $k$ in bid $j$ of buyer $I$, $C_k$ is the supply capacity of seller for specific item $k$, $N_{max,k}$ is the maximum number of selected buyers for a specific item k, and $D_{min,k}$ is the minimum allocation volume per buyer for a specific item $k$, $R_k$ is the reserve price for item $k$ of the seller. The objective function (7) corresponds to the goal of maximizing total sales. Constraint (8) and (9) correspond to the constraint maximum number of winning buyers. Constraint (10) corresponds to the constraint minimum allocation volume per buyer. Constraint (11) corresponds to the constraint supply capacity. Constraint (12) corresponds to the reserve unit price. Constraint (13) corresponds to the constraint ***XOR***. Constraint (14) and (15) are binary condition for the decision variables, which is a mandatory constraint for the bidder selection model.

## Conclusions

In this study, we presents an integrated and systematic framework for combinatorial auction design methodology. It is composed of three phases: architecture design, protocol design, and trading strategy design. The methodology can serve as a guide for effective design and practical implementation of combinatorial auction markets. In particular, we illustrate an n-bilateral combinatorial auction market, derived from our design methodology, to show the viability of our study.

The proposed design methodology serves as a framework that characterizes the different combinatorial auction models, and leads to a useful taxonomy of the combinatorial auction design factors and a taxonomy of the market types by coordination among the design factors. In addition, the methodology provides natural steps as a guide to make a new market model by suggesting design factors and alternatives that should be considered in dynamic market modeling process. In addition, by adopting the three phase model, we could develop a flexible and extensible framework that supports a comprehensive range of combinatorial auctions. Although we propose a comprehensive design methodology for supporting all combinatorial auction models, much work is still needed to extend the results for a more rigorous and practical method. Furthermore, we are planning a decision support system to show the viability of our design methodology. Through this, we can derive a coordinated combinatorial auction design, and we can support flexible model adaptation [9, 11] for the partner selection modeling.

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