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# BERTH ALLOCATION AT PASSENGER TERMINALS USING AUCTIONS

by

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A Dissertation

Submitted in Partial Fulfillment of the

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# Preface

This dissertation is submitted for the degree of Doctor of Philosophy at the University of Memphis. The research presented herein was conducted under the supervision of Dr. Mihalis Golias, Department of Civil Engineering, The University of Memphis.

The following published article has been used as chapter in this manuscript:

Chapter 2: Giampouranis, Dimitrios K., Mihalis Golias, Sotirios Theofanis, and Maria Boile. 2022. "Berth Allocation at Passenger Terminals Using Auctions" Journal of Marine Science and Engineering 10, no. 8: 1010. https://doi.org/10.3390/jmse10081010

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# Abstract

Both the industry/commercial community and academic circles have long recognized the necessity for developing an efficient and dependable system for allocating berth and quay slots at seaports. The majority of scholarly articles, however, deal with container ports, where berth allocation is often done on a first-come, first-served basis and/or based on long-term contracts. Although the berth allocation problem has been extensively studied and documented, it seems that few studies have been published with reference to auctions as the primary method of efficiently allocating berthing timeslots at passenger terminals. Previous studies have recognized the advantages that game theory and auctions have to offer in designing an efficient berth allocation scheme. The remaining question is whether, in the context of public berth allocation, it is more beneficial to employ a sequential item auction as opposed to a bundle auction. The goal of this study is to design different types of auction mechanisms in order to maximize the port operator's profits under different assumptions of supply and demand and compare them for their efficiency. The results from this study can be used by terminal operators, given their knowledge and/or assumptions on slot valuations and demand, to select a winner-determination policy and auction mechanism when designing their berth scheduling to maximize their profits.

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## 1. Introduction

Both the industry/commercial community and academic circles have long recognized the necessity for developing an efficient and dependable system for allocating berth and quay slots at seaports. The majority of scholarly articles, however, deal with container ports, where berth allocation is often done on a first-come, first-served basis and/or based on long term contracts (which establishes restrictions on vessel wait periods, departure schedules, and berth productivity). Some of these methods have been criticized for being uncompetitive for port operators and giving high-volume liner shipping companies preferential treatment [1-6]. Furthermore, these methods oftentimes lead to increased costs from fuel consumption and labor-related costs while a vessel waits for the next available slot at a port's entrance, increased traffic inside and around nearby seaports, delayed deliveries, etc. Bulow and Klemperer [7] came to the conclusion that, under certain conditions, an auction will always result in higher payoffs for the seller (terminal operator or port authority in the case of marine terminals), if it includes one or more participants (vessel operators/owners) than a direct negotiation on the same object. That is, if a port operator negotiates with a roll-on/roll-off passenger (RoPax) or cruise company, an effectively structured auction with at least two participants will result in greater payouts for the port/terminal operator owing to the increased degree of competition and to the properties of auction-based allocation (as will be discussed below). Furthermore, Theys et al. [8] concluded that studying the significance of various types of auctions for the awarding of berth at seaport terminals is crucial and highlighted that this conclusion is consistent with empirical data demonstrating the importance of creating and deploying proper auction types in other industries.

Although the berth-allocation problem has been extensively studied and documented, it seems that only a few studies have been published with reference to auctions as the primary method of efficiently allocating berthing time slots. Note that extensive research has been published on the strategic/tactical berth-scheduling problem in public and private terminals, which resembles the problem studied herein [9-12]. In those studies, container terminals are the subject of concern, and the labels "public" and "private" relate to the port administration and ownership models (i.e., a private terminal is run by a private corporation, often a liner shipping company [14]). To the author’s knowledge, no method in the literature that was proposed for allocating berth space to ships at passenger terminals (RoPax vessels and/or cruise ships) employed auctions as the main mechanism.

The effectiveness of a sequential English auction for queue management was examined by Gosh [1]. This auction procedure relied on the assumption that every bidder had the same preferences and ranked every vacant slot in the same order. Strandenes and Wolfstetter [14] claimed that group auctioning, designed with the requirement that bidders must disclose to the port operator predicted earnings from every possible allocation, is more effective for solving the berth allocation problem than single-slot auctioning. It was the port operator's responsibility to select an allocation that maximized the gains for each bidder. The proposed method by Strandenes and Wolfstetter [14] has a drawback in that each bidder must report profits from every feasible allocation to the port operator, rendering the problem intractable in real-life circumstances. By not requiring the bidders to report earnings, our proposed method solves this problem.

When focusing on passenger (cruise and roll on/roll off a passenger or RoPax) terminals most major ports’ berthing policies are similar. The port authority chooses the berth allocation and makes it known for a set amount of time (e.g., 6 months). New reservation requests must be placed in advance (with time varying by port, from six months to four years). The size of the vessel and its nautical, operational, and economic characteristics are the main factors in deciding the berth allocation [15–18]. The port/terminal operator often assigns all berths, while cruise/ferry operators have only restricted rights to choosing a particular berth. By providing cruise/ferry companies the choice to compete against one another for their desired berth spaces, we give port/terminal operators the chance to evaluate various berthing rules that optimize their revenues. For ferry and cruise companies, factors including accessibility to public transit, time of day, season, and proximity to parking spaces are essential. In this paper, we propose and compare a multi-round second-price sealed-bid bundle auction and a single-item multi-round sequential auction, as an alternative to the policies mentioned above, for the assignment of vessels at the berths of a public passenger/cruise terminal.

According to the berth-scheduling literature, when at least one more bidder enters the auction, employing an auction produces better outcomes than negotiations [7]. The remaining issue is whether, in the context of public-berth allocation, it is more beneficial to employ a single-item or a bundle-auction framework?

The rest of this dissertation is structured as follows: Chapter 2 describes the model formulation, methodology, numerical experiments, and results of the two proposed auction frameworks when time and space (i.e., berth length) are discrete variables. Chapter 3 introduces the concept of continuous berth length and describes changes in model formulation, methodology, numerical experiments, and results. The last part of this dissertation presents conclusions for both Chapter 2 and B as well as potential future research directions that stem from this study.

## 2. Discrete Berth Length

### Problem Description

In this section, we propose and evaluate a multi-item (berth and time slot), second-price auction framework to allocate berth space assuming the length of the berth as well as time are discrete variables. The proposed framework is compared against a single-item, sequential, second-price auction.

### Methodology

### Single-Item Auction

Under the single-item sequential second-price auction (from now on referred to as single-item auction), the port operator auctions each slot sequentially, where the winner for each slot is determined by their highest bid and the price paid to the port operator is equal to the second-highest bid. The sequence with which the slots become available for bidding is important for the outcome of the auction. We assume that the port operator has some knowledge of demand and berth location preference (from experience) and can thus prioritize the auction with slots that they believe are of higher value and will increase the competition amongst bidders. To start the auction, the port operator makes the first time-slot available for bidding. After the bidding ends, the winner and the price to be paid are determined. The first-round ends with the slot being removed from the pool of available slots. If the demand of the winner has been satisfied, the winner is removed from the pool of available bidders. The process continues until the demand has been met or the supply has been depleted. Figure 1 presents the steps of the single-item auction used in Chapter 2.

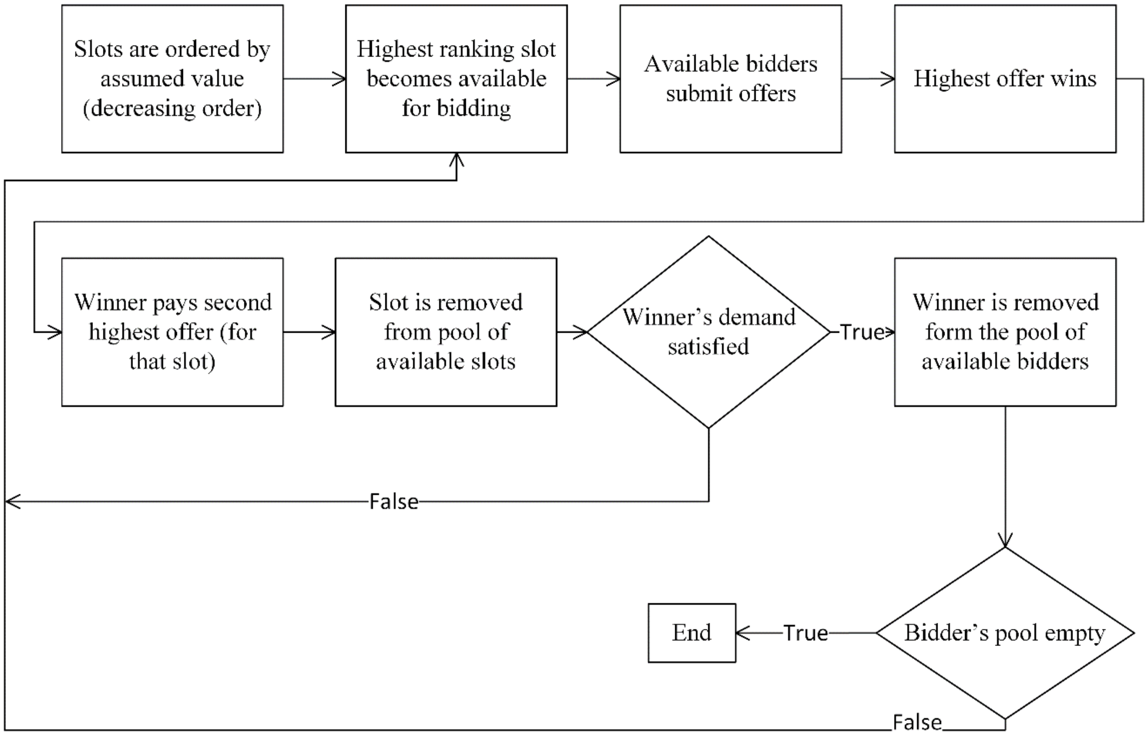


**Figure 1. Single-Item Auction Flowchart**

## Bundle Auction

The multi-round, second-price, sealed-bid bundle auction (from now on referred to as a bundle auction) proposed in this section (as an alternative to the single-item auction) auctions all available slots at the same time, and each player bids for the slots they need. Therefore, each bidder's offer includes only the slots they need with their highest valuation. At each round, the player with the highest bid wins the round and takes all the slots they bid for, paying the second-highest offer, regardless of what slots the second-highest offer was made. In this part, we evaluate two different winner-determination policies (i.e., how the highest bid is estimated), described in more detail later in this section. The winner is removed from the pool of remaining players along with the slots they acquired, and the remaining bidders resubmit bids for the available slots. The procedure is terminated when all players have received slots or there are no more slots available. At each round, a reserve price is introduced for the slots that have not been awarded. A reserve price is defined as the minimum price that the auctioneer will accept as a winning bid. The reserve price for each slot is calculated based on the mean profit made from all the winning bids in all previous rounds. We adopt a reserve price to address situations where a second-best price for a slot (or bundle of slots) does not exist (i.e., at the last round where only one player exists). Thus, the reserve price, in the way the proposed auction is set up, is only used at the last round of the auction. In that case, the winner will pay a reserve price for the slots awarded, so that their profit equals the mean profit of all the previous winners. Note that in the proposed auction a reserve price does not alter the behavior of the bidders (i.e., it is still a dominant strategy to bid one’s true valuation), since if the reserve price was higher than the bid, the bidder will not take the slot, and their expected payoffs will be zero. Figure 2 presents the steps of the bundle auction.

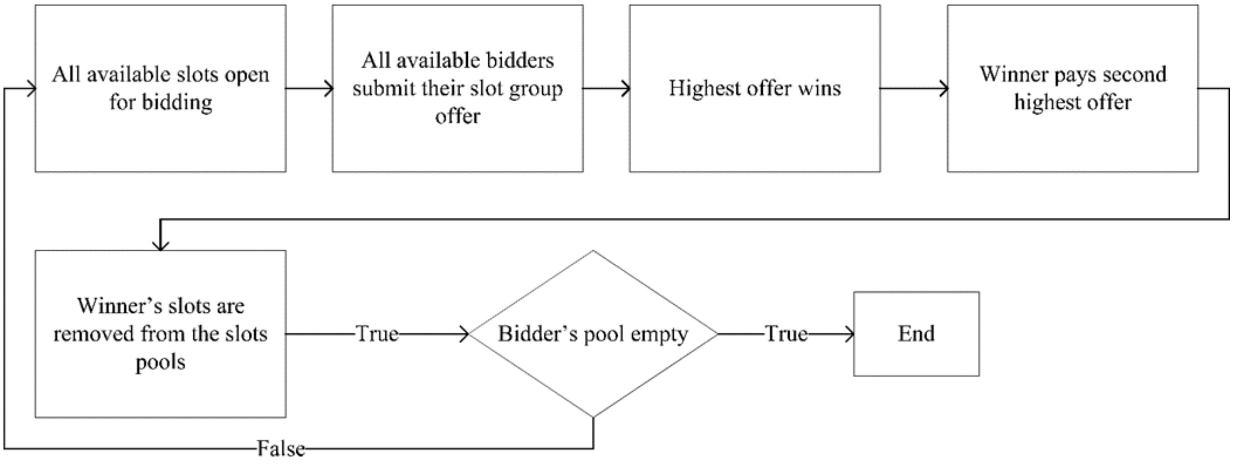


**Figure 2. Bundle Auction Flowchart**

### Rationale for Second-Price Bundle Auction

Standard auctions (e.g., English auction where each slot is auctioned sequentially) have been examined in the related literature, but they are generally inefficient [13]. In the auction scheme proposed herein, we utilize the advantages of a second-price bundle or single auction. We require that the proposed mechanisms satisfy the voluntary participation condition, where players are not charged if they lose, and their (expected) payoffs are at most the second-highest bid if they win [19]. In a second-price auction, it is a dominant strategy to bid the maximum valuation price of the object auctioned, even if other bidders are over-bidding, under-bidding, or colluding. This guarantees that players who bid truthfully always obtain non-negative (expected) profit, and as in other Vickrey–Clarke– Groves auctions, a second-price, sealed-bid auction guarantees truthfulness. As with many game theory applications, in real life, truthfulness might not be guaranteed due to the players irrational behavior. Since a second-price auction always guarantees that the player will end up with non-negative profits for the item(s) they are awarded, it encourages even irrational players to bid truthfully.

### Auction Assumptions

To apply the proposed auctions, the following assumptions are made:

- The supply of slots by the port operator is greater than (or at least equal to) the demand by the bidders (applied on three out of four simulations described in the next section).

- There is imperfect information, i.e., bidders are unaware of each other's valuation for each slot and for what slots they will bid.

- A possible situation where a bidder bids for more slots than they need, to improve their position against the competition, is allowed since we are interested in maximizing the port operator's profits and not in an equitable distribution of resources.

## Slot Valuation Patterns

In this study, we assumed two different slot valuation patterns for each slot and bidder to be used in the simulation experiments presented in the next section: random and uniform. Next, we describe the assumptions made behind both slot valuation patterns.

### *Random Valuation Pattern (RVP)*

Under the RVP, each bidder has their own valuation for each slot which has been assigned randomly. That means that a certain slot might be of high value for one player and of low value for another. This is a more generic way to determine each slot's valuation by every bidder. This case would represent the case of off-peak season or off-peak days of the week.

### *Uniform Valuation Pattern (UVP)*

Under the UVP, the value of each slot is based on a uniform probability distribution. That is, all bidders have similar valuations for each slot. This does not mean that the valuation for different slots is the same (i.e., players will give higher value to slots at peak demand periods and lower slots at low demand periods, but their valuations at each period will be similar). This version of slot valuation allows for high competition between the bidders for the most desirable slots and, possibly, increases the port operator's profits since, in each round, the second-highest bid (i.e., price that the winner will pay) is close to the highest bid (i.e., winner's bid).

## Winner Determination

To determine the winning bid of each round of the proposed auction, we propose two different policies, described next.

### *Winner Determination Policy Based on the Total Bid (MWD)*

Under the MWD policy, the winner is determined based on the highest total bid over all the slots, regardless of how many slots a player has bid for. Let S be the set of all available slots and V(Si) be the valuations of player i for the subset of slots Si ⊆ S. Assume that players i and j bid for a subset of slots Si and Sj (Si, Sj ⊆ S). Then if V(Si) ≥ V(Sj) player i will win the bid and be awarded the subset of slots Si. This winner determination policy provides a significant advantage to players that bid for many slots at the same time and/or are willing to pay a higher amount. In case of a tie (V(Si) = V(Sj)), the winner is the player with the lowest number of slots (i.e., the bidder with the highest average per slot bid). In case of a tie for both the bid price (V(Si) = V(Sj)) and number of slots (|Si| = |Sj|), the winner is chosen randomly.

### *Winner Determination Policy Based on the Average Bid per Slot (AWD)*

Under the AWD policy, the winner is determined based on the highest average per slot bid. For example, if bidders i and j offer V(Si) and V(Sj) for slots Si and Sj, respectively, the player with the highest valuation to number of slots ratio (i.e., (V(Si))/(|Si|), (V(Sj))/(|Sj|)) is the winner. In case of a tie, the winner is chosen based on the number of slots they bid for, but in this case, and in antithesis with MWD, the bidder with the highest number of slots wins.

## Numerical Experiments

In this section, we present results from a set of numerical experiments, performed using Monte Carlo simulation, to compare the proposed multi-round second price sealed- bid bundle auction to the single-item, sequential, second-price auction. We simulated four different demand/supply scenarios by varying assumptions on the slot valuation pattern, number of bidders, and slot demand by each bidder. For every scenario, we simulated 10,000 auctions for each winner determination policy (i.e., MWD and AWD) and slot valuation pattern (i.e., RVP and UVP) combination for both the single and bundle auctions. In all numerical experiments, the number of available slots has been set to 300. Next, we present a detailed description of each scenario:

a. Base Scenario: Under this scenario, valuations for each slot by each bidder were uniformly distributed between twenty and one hundred. We considered six distinct cases with respect to the number of bidders, ranging from five to ten. We also considered seven distinct cases for the minimum number of slots a player will bid for, ranging from three to nine. We also considered three distinct cases for the maximum number of slots a player would bid for. These were calculated based on a uniform distribution with a lower bound equal to the minimum number of slots a player would bid for and an upper bound equal to one, two, and three times that minimum (i.e., if the minimum number of slots a player will bid for is X, then the bidders can bid for any number of slots between U[X, X], U[X,2X], and U[X, 3X], respectively, where U[a, b] is the uniform distribution with bounds a and b). A total of 504 unique combinations of winner determination, slot valuation, and demand patterns were created. Under the base scenario, we assumed that supply was greater or equal to the demand (i.e., the total number of available slots is greater or equal to the total number of slots requested by the bidders).

b. Group Demand Scenario: Under this scenario, we created three distinct groups of bidders based on the number of slots (i.e., demand) they request. Approximately one-third of bidders are considered ‘weak’, meaning they will only bid for the minimum number of slots allowed. The second third of the bidders have medium competitiveness and bid for double the minimum number of slots allowed. The final subset of bidders bid for the maximum number of slots allowed and are considered as ‘strong’. The rest of the assumptions remain the same as in the base scenario. This additional scenario is used to evaluate the case where players can be grouped into distinct subsets based on their strength as defined by the number of slots they are seeking.

c. Group Valuation Scenario: Under this scenario, the available slots are divided into three distinct subsets based on the slot valuation of all bidders. For all bidders, one-third of the same available slots have a uniformly distributed valuation between twenty and forty, one-third between fifty and seventy, and one-third between eighty and one hundred. The rest of the assumptions remain the same as in the base scenario. This additional scenario is used to evaluate the case where slot valuations can be grouped in subsets for all players (e.g., AM period has a high, MD a medium, and PM a low valuation for all players).

d. Insufficient Supply Scenario: Under this scenario, we assume that the number of bidders is equal to twenty. Under this scenario, and for the cases where the minimum slot bid for any bidder is greater or equal to eight, the available slots are not enough to satisfy the demand for all bidders. The other assumptions remain the same as in the base scenario. This additional scenario is used to evaluate the effects of insufficient supply.

## Results

Next, we present and discuss results from the simulation of the four different scenarios. Table 1 through Table 8 summarize the results the single and bundle auctions. The results are presented as the mean percentage change in profits for the port operator when the bundle auction is used instead of the single for each simulation scenario. Table 1 shows the terminal operator’s mean profit change for the general simulation scenario for U[X,X], U[X,2X], and U[X,3X], respectively; Table 3 for the demand group scenario; Table 5 for the group valuation scenario; and Table 7 for the insufficient supply scenario. For consistency purposes, we show results for the minimum slot bid of three through seven, even though under these minimum slot bids there is sufficient supply. Table 2, Table 4, Table 6, and Table 8 show the standard deviation for each scenario, respectively. The assumption of normality was tested visually through histograms and with the Anderson–Darling test [20]. In addition to the results presented in Table 1 through Table 8, we also estimated the coefficient of variation (CoV) of the mean profit difference between the two auctions to evaluate the relative dispersion of the results around the mean. For the Base Scenario, the CoV was approximately 58% irrespective of the min/max slot bid ratio (i.e., U[X,X], U[X,2X], and U[X,3X]). For the Group Demand Scenario, the CoV was 58%. Finally, the Group Valuation Scenario had a CoV of 56%, and the Insufficient Supply Scenario had a CoV of 71%. Additionally, for Table 1,Table 3Table 3, Table 5, and Table 7, the red color indicates that the port operator would be better off using the sequential auction while green flags those cases in which the port operator would be better off using the bundle approach.

## Table 1. Base Scenario Mean Profit Difference: Bundle VS Single Item Auction

| Min Slot Bid | number of slots a player would bid for U(X,X) | | | | | | number of slots a player would bid for U(X,2X) | | | | | | number of slots a player would bid for U(X,3X) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Bidders | | | | | | Number of Bidders | | | | | | Number of Bidders | | | | | |
| | 5 | 6 | 7 | 8 | 9 | 10 | 5 | 6 | 7 | 8 | 9 | 10 | 5 | 6 | 7 | 8 | 9 | 10 |
| | MWD | | | | | | | | | | | | | | | | | |
| | Table 1a | | | | | | Table 1b | | | | | | Table 1c | | | | | |
| 3 | 12% | 12% | 12% | 11% | 11% | 10% | 4% | 6% | 6% | 6% | 6% | 6% | 0% | 2% | 2% | 3% | 3% | 3% |
| 4 | 11% | 11% | 11% | 11% | 10% | 10% | 3% | 4% | 5% | 5% | 5% | 5% | -1% | 1% | 2% | 2% | 2% | 2% |
| 5 | 11% | 11% | 11% | 10% | 10% | 9% | 3% | 4% | 4% | 5% | 4% | 4% | -1% | 1% | 1% | 2% | 2% | 2% |
| 6 | 10% | 10% | 10% | 10% | 9% | 9% | 2% | 3% | 4% | 4% | 4% | 4% | -1% | 0% | 1% | 2% | 2% | 2% |
| 7 | 10% | 10% | 10% | 9% | 9% | 8% | 2% | 3% | 4% | 4% | 4% | 4% | -2% | 0% | 1% | 1% | 2% | 2% |
| 8 | 9% | 10% | 9% | 9% | 9% | 8% | 2% | 3% | 3% | 4% | 4% | 4% | -2% | 0% | 1% | 1% | 1% | 1% |
| 9 | 9% | 9% | 9% | 9% | 8% | 8% | 1% | 3% | 3% | 3% | 3% | 3% | -2% | 0% | 0% | 1% | 1% | 1% |
| | AWD | | | | | | | | | | | | | | | | | |
| 3 | 12% | 12% | 12% | 11% | 11% | 10% | 10% | 11% | 11% | 10% | 10% | 9% | 10% | 10% | 10% | 10% | 9% | 9% |
| 4 | 11% | 11% | 11% | 11% | 10% | 10% | 10% | 10% | 10% | 10% | 9% | 9% | 9% | 10% | 10% | 9% | 9% | 9% |
| 5 | 11% | 11% | 11% | 10% | 10% | 9% | 9% | 10% | 10% | 9% | 9% | 8% | 9% | 9% | 9% | 9% | 9% | 8% |
| 6 | 10% | 10% | 10% | 10% | 9% | 9% | 9% | 9% | 9% | 9% | 8% | 8% | 8% | 9% | 9% | 9% | 8% | 8% |
| 7 | 10% | 10% | 10% | 9% | 9% | 8% | 8% | 9% | 9% | 9% | 8% | 8% | 8% | 8% | 8% | 8% | 8% | 7% |
| 8 | 9% | 10% | 9% | 9% | 9% | 8% | 8% | 9% | 9% | 8% | 8% | 8% | 8% | 8% | 8% | 8% | 8% | 7% |
| 9 | 9% | 9% | 9% | 9% | 8% | 8% | 8% | 8% | 8% | 8% | 8% | 7% | 7% | 8% | 8% | 8% | 7% | 7% |

UNIFORM VALUATION PATTERN

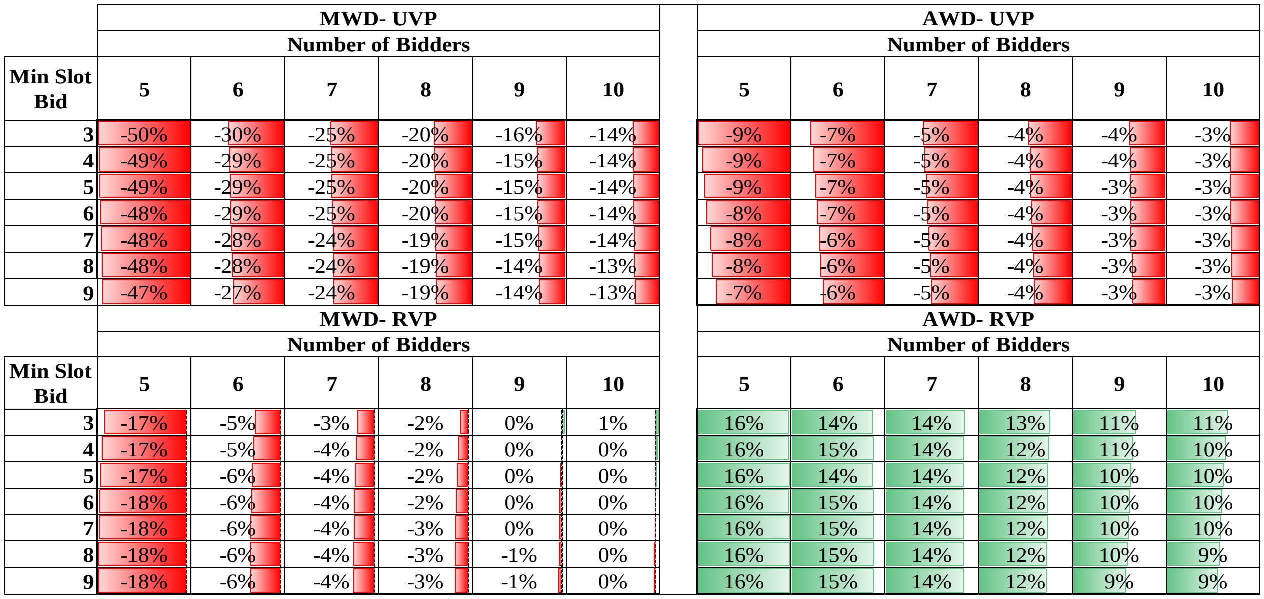
| Min Slot Bid | number of slots a player would bid for U(X,X) | | | | | | number of slots a player would bid for U(X,2X) | | | | | | number of slots a player would bid for U(X,3X) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Bidders | | | | | | Number of Bidders | | | | | | Number of Bidders | | | | | |
| | 5 | 6 | 7 | 8 | 9 | 10 | 5 | 6 | 7 | 8 | 9 | 10 | 5 | 6 | 7 | 8 | 9 | 10 |
| | MWD | | | | | | | | | | | | | | | | | |
| | Table 1d | | | | | | Table 1e | | | | | | Table 1f | | | | | |
| 3 | -12% | -8% | -6% | -5% | -4% | -3% | -20% | -15% | -11% | -9% | -8% | -7% | -25% | -19% | -15% | -13% | -11% | -10% |
| 4 | -12% | -8% | -6% | -4% | -4% | -3% | -20% | -15% | -12% | -10% | -8% | -7% | -25% | -19% | -16% | -13% | -11% | -10% |
| 5 | -12% | -8% | -6% | -4% | -3% | -3% | -20% | -15% | -12% | -10% | -8% | -7% | -25% | -19% | -15% | -13% | -11% | -10% |
| 6 | -12% | -8% | -6% | -4% | -3% | -3% | -20% | -15% | -12% | -10% | -8% | -7% | -25% | -19% | -15% | -13% | -11% | -10% |
| 7 | -12% | -8% | -6% | -4% | -3% | -3% | -20% | -15% | -12% | -10% | -8% | -7% | -25% | -19% | -15% | -13% | -11% | -10% |
| 8 | -12% | -8% | -6% | -4% | -3% | -3% | -20% | -15% | -12% | -10% | -8% | -7% | -25% | -19% | -15% | -13% | -11% | -9% |
| 9 | -12% | -8% | -6% | -4% | -3% | -3% | -20% | -15% | -12% | -10% | -8% | -7% | -25% | -19% | -15% | -12% | -11% | -9% |
| | AWD | | | | | | | | | | | | | | | | | |
| 3 | -12% | -8% | -6% | -5% | -4% | -3% | -12% | -8% | -6% | -5% | -4% | -3% | -13% | -9% | -6% | -5% | -4% | -3% |
| 4 | -12% | -8% | -6% | -4% | -4% | -3% | -12% | -8% | -6% | -5% | -4% | -3% | -13% | -9% | -6% | -5% | -4% | -3% |
| 5 | -12% | -8% | -6% | -4% | -3% | -3% | -12% | -8% | -6% | -5% | -4% | -3% | -13% | -9% | -6% | -5% | -4% | -3% |
| 6 | -12% | -8% | -6% | -4% | -3% | -3% | -12% | -8% | -6% | -4% | -3% | -3% | -13% | -9% | -6% | -5% | -4% | -3% |
| 7 | -12% | -8% | -6% | -4% | -3% | -3% | -12% | -8% | -6% | -4% | -3% | -3% | -13% | -9% | -6% | -5% | -4% | -3% |
| 8 | -12% | -8% | -6% | -4% | -3% | -3% | -12% | -8% | -6% | -4% | -3% | -3% | -13% | -9% | -6% | -4% | -3% | -3% |
| 9 | -12% | -8% | -6% | -4% | -3% | -3% | -12% | -8% | -6% | -4% | -3% | -3% | -13% | -8% | -6% | -4% | -3% | -3% |

## Table 2. Base Scenario Standard Deviation: Bundle VS Single Item Auction

**RANDOM VALUATION PATTERN**

| Min Slot Bid | number of slots a player would bid for U(X,X) | | | | | | number of slots a player would bid for U(X,2X) | | | | | | number of slots a player would bid for U(X,3X) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Bidders | | | | | | Number of Bidders | | | | | | Number of Bidders | | | | | |
| | 5 | 6 | 7 | 8 | 9 | 10 | 5 | 6 | 7 | 8 | 9 | 10 | 5 | 6 | 7 | 8 | 9 | 10 |
| | MWD | | | | | | | | | | | | | | | | | |
| | Table 1a | | | | | | Table 1b | | | | | | Table 1c | | | | | |
| 3 | 6.42 | 4.78 | 3.94 | 3.28 | 2.80 | 2.49 | 5.00 | 2.98 | 1.98 | 1.40 | 1.00 | 0.79 | 5.53 | 3.32 | 2.22 | 1.58 | 1.18 | 0.91 |
| 4 | 5.80 | 4.33 | 3.44 | 2.88 | 2.41 | 2.12 | 5.06 | 2.98 | 1.99 | 1.39 | 1.03 | 0.78 | 5.52 | 3.36 | 2.25 | 1.57 | 1.19 | 0.93 |
| 5 | 5.50 | 3.94 | 3.08 | 2.53 | 2.15 | 1.93 | 4.98 | 2.94 | 1.99 | 1.39 | 1.02 | 0.79 | 5.61 | 3.38 | 2.22 | 1.57 | 1.20 | 0.93 |
| 6 | 5.24 | 3.75 | 2.91 | 2.35 | 2.00 | 1.74 | 5.00 | 2.99 | 1.98 | 1.39 | 1.02 | 0.80 | 5.52 | 3.37 | 2.23 | 1.59 | 1.18 | 0.92 |
| 7 | 5.12 | 3.60 | 2.70 | 2.22 | 1.88 | 1.62 | 4.97 | 2.97 | 1.96 | 1.36 | 1.02 | 0.79 | 5.53 | 3.31 | 2.21 | 1.59 | 1.18 | 0.92 |
| 8 | 4.91 | 3.42 | 2.59 | 2.08 | 1.76 | 1.53 | 5.00 | 2.97 | 1.94 | 1.36 | 1.01 | 0.79 | 5.59 | 3.30 | 2.20 | 1.58 | 1.18 | 0.92 |
| 9 | 4.76 | 3.29 | 2.50 | 2.01 | 1.67 | 1.44 | 4.95 | 3.00 | 1.95 | 1.34 | 1.00 | 0.79 | 5.50 | 3.34 | 2.20 | 1.56 | 1.18 | 0.93 |
| | AWD | | | | | | | | | | | | | | | | | |
| 3 | 6.42 | 4.78 | 3.94 | 3.28 | 2.80 | 2.49 | 5.75 | 4.10 | 3.23 | 2.66 | 2.24 | 1.99 | 5.80 | 4.08 | 3.12 | 2.58 | 2.16 | 1.86 |
| 4 | 5.80 | 4.33 | 3.44 | 2.88 | 2.41 | 2.12 | 5.41 | 3.83 | 2.93 | 2.43 | 2.03 | 1.78 | 5.60 | 3.89 | 2.95 | 2.38 | 1.96 | 1.73 |
| 5 | 5.50 | 3.94 | 3.08 | 2.53 | 2.15 | 1.93 | 5.25 | 3.64 | 2.79 | 2.25 | 1.89 | 1.62 | 5.53 | 3.74 | 2.81 | 2.24 | 1.86 | 1.59 |
| 6 | 5.24 | 3.75 | 2.91 | 2.35 | 2.00 | 1.74 | 5.06 | 3.48 | 2.65 | 2.12 | 1.76 | 1.51 | 5.48 | 3.65 | 2.77 | 2.15 | 1.78 | 1.52 |
| 7 | 5.12 | 3.60 | 2.70 | 2.22 | 1.88 | 1.62 | 5.05 | 3.40 | 2.57 | 2.04 | 1.69 | 1.44 | 5.35 | 3.63 | 2.65 | 2.10 | 1.74 | 1.46 |
| 8 | 4.91 | 3.42 | 2.59 | 2.08 | 1.76 | 1.53 | 4.98 | 3.40 | 2.48 | 1.98 | 1.63 | 1.38 | 5.40 | 3.58 | 2.63 | 2.06 | 1.68 | 1.40 |
| 9 | 4.76 | 3.29 | 2.50 | 2.01 | 1.67 | 1.44 | 4.90 | 3.29 | 2.44 | 1.90 | 1.56 | 1.34 | 5.29 | 3.52 | 2.56 | 2.02 | 1.66 | 1.41 |
| | UNIFORM VALUATION PATTERN | | | | | | | | | | | | | | | | | |
| Min Slot Bid | number of slots a player would bid for U(X,X) | | | | | | number of slots a player would bid for U(X,2X) | | | | | | number of slots a player would bid for U(X,3X) | | | | | |
| | Number of Bidders | | | | | | Number of Bidders | | | | | | Number of Bidders | | | | | |
| | 5 | 6 | 7 | 8 | 9 | 10 | 5 | 6 | 7 | 8 | 9 | 10 | 5 | 6 | 7 | 8 | 9 | 10 |
| | MWD | | | | | | | | | | | | | | | | | |
| | Table 1d | | | | | | Table 1e | | | | | | Table 1f | | | | | |
| 3 | 4.68 | 2.81 | 1.82 | 1.27 | 0.94 | 0.72 | 6.14 | 3.83 | 2.58 | 1.90 | 1.42 | 1.12 | 8.07 | 5.33 | 3.80 | 2.94 | 2.31 | 1.93 |
| 4 | 4.69 | 2.77 | 1.79 | 1.27 | 0.92 | 0.70 | 6.15 | 3.87 | 2.70 | 2.00 | 1.56 | 1.25 | 8.19 | 5.35 | 3.87 | 3.04 | 2.40 | 2.02 |
| 5 | 4.69 | 2.78 | 1.82 | 1.23 | 0.91 | 0.69 | 6.12 | 3.85 | 2.72 | 2.02 | 1.61 | 1.32 | 8.11 | 5.38 | 3.94 | 3.04 | 2.47 | 2.03 |
| 6 | 4.61 | 2.70 | 1.80 | 1.23 | 0.93 | 0.68 | 6.04 | 3.93 | 2.71 | 2.03 | 1.63 | 1.35 | 8.21 | 5.43 | 4.08 | 3.10 | 2.51 | 2.06 |
| 7 | 4.61 | 2.73 | 1.76 | 1.23 | 0.90 | 0.68 | 6.05 | 3.85 | 2.73 | 2.05 | 1.65 | 1.39 | 8.16 | 5.44 | 4.00 | 3.11 | 2.55 | 2.09 |
| 8 | 4.52 | 2.69 | 1.73 | 1.25 | 0.89 | 0.67 | 6.01 | 3.86 | 2.76 | 2.11 | 1.67 | 1.39 | 8.18 | 5.37 | 4.01 | 3.09 | 2.53 | 2.15 |
| 9 | 4.51 | 2.68 | 1.75 | 1.21 | 0.88 | 0.67 | 5.98 | 3.89 | 2.76 | 2.09 | 1.69 | 1.40 | 8.23 | 5.46 | 4.05 | 3.15 | 2.57 | 2.18 |
| | AWD | | | | | | | | | | | | | | | | | |
| 3 | 4.68 | 2.81 | 1.82 | 1.27 | 0.94 | 0.72 | 6.51 | 4.67 | 3.61 | 2.92 | 2.45 | 2.15 | 7.42 | 5.15 | 3.97 | 3.23 | 2.71 | 2.29 |
| 4 | 4.69 | 2.77 | 1.79 | 1.27 | 0.92 | 0.70 | 6.22 | 4.40 | 3.36 | 2.69 | 2.27 | 1.97 | 7.13 | 4.99 | 3.82 | 3.00 | 2.52 | 2.16 |
| 5 | 4.69 | 2.78 | 1.82 | 1.23 | 0.91 | 0.69 | 6.02 | 4.18 | 3.17 | 2.57 | 2.16 | 1.83 | 6.90 | 4.83 | 3.65 | 2.91 | 2.38 | 2.02 |
| 6 | 4.61 | 2.70 | 1.80 | 1.23 | 0.93 | 0.68 | 5.85 | 4.06 | 3.06 | 2.46 | 2.03 | 1.73 | 6.90 | 4.68 | 3.48 | 2.78 | 2.28 | 1.94 |
| 7 | 4.61 | 2.73 | 1.76 | 1.23 | 0.90 | 0.68 | 5.73 | 3.93 | 2.94 | 2.35 | 1.95 | 1.66 | 6.84 | 4.59 | 3.41 | 2.69 | 2.22 | 1.86 |
| 8 | 4.52 | 2.69 | 1.73 | 1.25 | 0.89 | 0.67 | 5.62 | 3.87 | 2.88 | 2.27 | 1.89 | 1.60 | 6.69 | 4.51 | 3.35 | 2.67 | 2.16 | 1.79 |
| 9 | 4.51 | 2.68 | 1.75 | 1.21 | 0.88 | 0.67 | 5.61 | 3.83 | 2.79 | 2.20 | 1.81 | 1.54 | 6.61 | 4.49 | 3.30 | 2.60 | 2.12 | 1.75 |

## Table 3. Mean Profit Difference for Group Demand Scenario



| | MWD- UVP | | | | | | AWD- UVP | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Bidders | | | | | | Number of Bidders | | | | | |
| **Min Slot Bid** | **5** | **6** | **7** | **8** | **9** | **10** | **5** | **6** | **7** | **8** | **9** | **10** |
| **3** | -50% | -30% | -25% | -20% | -16% | -14% | -9% | -7% | -5% | -4% | -4% | -3% |
| **4** | -49% | -29% | -25% | -20% | -15% | -14% | -9% | -7% | -5% | -4% | -4% | -3% |
| **5** | -49% | -29% | -25% | -20% | -15% | -14% | -9% | -7% | -5% | -4% | -3% | -3% |
| **6** | -48% | -29% | -25% | -20% | -15% | -14% | -8% | -7% | -5% | -4% | -3% | -3% |
| **7** | -48% | -28% | -24% | -19% | -15% | -14% | -8% | -6% | -5% | -4% | -3% | -3% |
| **8** | -48% | -28% | -24% | -19% | -14% | -13% | -8% | -6% | -5% | -4% | -3% | -3% |
| **9** | -47% | -27% | -24% | -19% | -14% | -13% | -7% | -6% | -5% | -4% | -3% | -3% |

| | MWD- RVP | | | | | | AWD- RVP | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Bidders | | | | | | Number of Bidders | | | | | |
| **Min Slot Bid** | **5** | **6** | **7** | **8** | **9** | **10** | **5** | **6** | **7** | **8** | **9** | **10** |
| **3** | -17% | -5% | -3% | -2% | 0% | 1% | 16% | 14% | 14% | 13% | 11% | 11% |
| **4** | -17% | -5% | -4% | -2% | 0% | 0% | 16% | 15% | 14% | 12% | 11% | 10% |
| **5** | -17% | -6% | -4% | -2% | 0% | 0% | 16% | 14% | 14% | 12% | 10% | 10% |
| **6** | -18% | -6% | -4% | -2% | 0% | 0% | 16% | 15% | 14% | 12% | 10% | 10% |
| **7** | -18% | -6% | -4% | -3% | 0% | 0% | 16% | 15% | 14% | 12% | 10% | 10% |
| **8** | -18% | -6% | -4% | -3% | -1% | 0% | 16% | 15% | 14% | 12% | 10% | 9% |
| **9** | -18% | -6% | -4% | -3% | -1% | 0% | 16% | 15% | 14% | 12% | 9% | 9% |

## Table 4. Standard Deviation for Group Demand Scenario

| | MWD- UVP | | | | | | AWD- UVP | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Bidders | | | | | | Number of Bidders | | | | | |
| **Min Slot Bid** | **5** | **6** | **7** | **8** | **9** | **10** | **5** | **6** | **7** | **8** | **9** | **10** |
| **3** | 0.81 | 0.64 | 0.61 | 0.56 | 0.52 | 0.51 | 5.56 | 4.02 | 2.87 | 1.99 | 1.52 | 1.25 |
| **4** | 0.89 | 0.73 | 0.69 | 0.63 | 0.59 | 0.58 | 5.60 | 4.08 | 2.89 | 2.02 | 1.53 | 1.25 |
| **5** | 0.97 | 0.81 | 0.76 | 0.70 | 0.65 | 0.64 | 5.59 | 4.07 | 2.92 | 2.01 | 1.53 | 1.26 |
| **6** | 1.05 | 0.88 | 0.81 | 0.75 | 0.71 | 0.69 | 5.63 | 4.10 | 2.93 | 2.02 | 1.54 | 1.27 |
| **7** | 1.11 | 0.94 | 0.88 | 0.80 | 0.77 | 0.73 | 5.56 | 4.09 | 2.92 | 2.00 | 1.53 | 1.27 |
| **8** | 1.18 | 0.99 | 0.95 | 0.87 | 0.81 | 0.79 | 5.51 | 4.08 | 2.92 | 2.02 | 1.52 | 1.26 |
| **9** | 1.26 | 1.05 | 0.99 | 0.91 | 0.84 | 0.84 | 5.46 | 4.04 | 2.90 | 1.98 | 1.53 | 1.29 |

| | MWD- RVP | | | | | | AWD- RVP | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Bidders | | | | | | Number of Bidders | | | | | |
| **Min Slot Bid** | **5** | **6** | **7** | **8** | **9** | **10** | **5** | **6** | **7** | **8** | **9** | **10** |
| **3** | 6.11 | 4.30 | 3.81 | 3.12 | 2.52 | 2.37 | 6.52 | 5.38 | 4.43 | 3.56 | 2.77 | 2.55 |
| **4** | 5.37 | 3.83 | 3.42 | 2.72 | 2.21 | 2.06 | 6.04 | 5.17 | 4.31 | 3.35 | 2.61 | 2.32 |
| **5** | 4.85 | 3.47 | 3.12 | 2.51 | 2.01 | 1.90 | 5.68 | 5.09 | 4.12 | 3.28 | 2.51 | 2.24 |
| **6** | 4.51 | 3.24 | 2.92 | 2.37 | 1.88 | 1.76 | 5.47 | 4.84 | 3.99 | 3.18 | 2.46 | 2.19 |
| **7** | 4.14 | 3.01 | 2.77 | 2.23 | 1.74 | 1.63 | 5.24 | 4.69 | 3.84 | 3.09 | 2.40 | 2.10 |
| **8** | 3.98 | 2.92 | 2.59 | 2.12 | 1.64 | 1.56 | 5.00 | 4.55 | 3.69 | 2.95 | 2.36 | 2.09 |
| **9** | 3.76 | 2.76 | 2.49 | 2.03 | 1.58 | 1.46 | 4.88 | 4.38 | 3.54 | 2.90 | 2.35 | 2.03 |

## Table 5. Mean Profit Difference for Group Valuation Scenario

| | MWD | | | | | | AWD | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Bidders | | | | | | Number of Bidders | | | | | |
| Min Slot Bid | 5 | 6 | 7 | 8 | 9 | 10 | 5 | 6 | 7 | 8 | 9 | 10 |
| 3 | -26% | -20% | -16% | -13% | -11% | -10% | -13% | -9% | -6% | -5% | -4% | -3% |
| 4 | -26% | -20% | -16% | -13% | -12% | -10% | -13% | -9% | -6% | -5% | -4% | -3% |
| 5 | -26% | -20% | -16% | -14% | -12% | -10% | -13% | -9% | -7% | -5% | -4% | -3% |
| 6 | -26% | -20% | -16% | -14% | -12% | -10% | -13% | -9% | -7% | -5% | -4% | -3% |
| 7 | -26% | -20% | -16% | -14% | -12% | -10% | -13% | -9% | -7% | -5% | -4% | -3% |
| 8 | -26% | -20% | -16% | -13% | -12% | -10% | -14% | -9% | -6% | -5% | -4% | -3% |
| 9 | -26% | -20% | -16% | -13% | -12% | -10% | -14% | -9% | -6% | -5% | -4% | -3% |

## Table 6. Standard Deviation for Group Valuation Scenario

| | MWD | | | | | | AWD | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Bidders | | | | | | Number of Bidders | | | | | |
| Min Slot Bid | 5 | 6 | 7 | 8 | 9 | 10 | 5 | 6 | 7 | 8 | 9 | 10 |
| 3 | 8.12 | 5.38 | 3.84 | 2.93 | 2.31 | 1.89 | 5.55 | 3.39 | 2.24 | 1.60 | 1.19 | 0.93 |
| 4 | 8.16 | 5.30 | 3.88 | 2.93 | 2.33 | 1.90 | 5.67 | 3.36 | 2.27 | 1.62 | 1.20 | 0.94 |
| 5 | 8.20 | 5.36 | 3.87 | 2.98 | 2.36 | 1.98 | 5.62 | 3.41 | 2.28 | 1.62 | 1.22 | 0.94 |
| 6 | 8.18 | 5.43 | 3.95 | 3.02 | 2.45 | 2.03 | 5.72 | 3.45 | 2.28 | 1.60 | 1.19 | 0.88 |
| 7 | 8.12 | 5.36 | 3.94 | 3.13 | 2.46 | 2.02 | 5.75 | 3.45 | 2.29 | 1.60 | 1.13 | 0.90 |
| 8 | 8.16 | 5.46 | 4.05 | 3.07 | 2.47 | 2.06 | 5.70 | 3.43 | 2.24 | 1.56 | 1.12 | 0.88 |
| 9 | 8.23 | 5.50 | 4.01 | 3.09 | 2.52 | 2.10 | 5.66 | 3.45 | 2.21 | 1.51 | 1.14 | 0.88 |

## Table 7. Mean Profit Difference for Insufficient Supply Scenario

| | MWD | | AWD | |
|---|---|---|---|---|
| Min Slot Bid | UVP | RVP | UVP | RVP |
| 3 | -4.7 | 2.6 | -0.8 | 6.1 |
| 4 | -4.9 | 2.2 | -0.8 | 5.7 |
| 5 | -5.1 | 1.9 | -0.8 | 5.2 |
| 6 | -5.2 | 1.6 | -0.8 | 4.6 |
| 7 | -5.5 | 1.1 | -0.9 | 3.3 |
| 8 | -6.3 | -2.2 | -2.0 | -1.5 |
| 9 | -6.7 | -4.8 | -1.9 | -3.5 |

**Table 8. Standard Deviation for Insufficient Supply Scenario**

| | MWD | | AWD | |
|---|---|---|---|---|
| **Min Slot Bid** | **UVP** | **RVP** | **UVP** | **RVP** |
| **3** | 0.49 | 0.94 | 0.25 | 0.89 |
| **4** | 0.57 | 0.88 | 0.30 | 0.81 |
| **5** | 0.62 | 0.80 | 0.34 | 0.75 |
| **6** | 0.65 | 0.76 | 0.37 | 0.73 |
| **7** | 0.66 | 0.81 | 0.42 | 0.93 |
| **8** | 0.79 | 1.18 | 0.96 | 1.73 |
| **9** | 0.87 | 1.06 | 1.14 | 2.05 |

The results shown in Table 1 through Table 8 reveal very distinctive patterns that can be summarized as follows:

- As the number of bidders and number of slots they bid for increases, the profit difference between the single and bundle auction is reduced, for the UVP cases. For the RVP cases, profit differences remain rather constant, favoring the bundle auction, except for the MWP with U(X,3X) (Table 1).
- For the cases of uniform valuation pattern, and irrespective of the winner determination policy, the terminal operator is better off using the single-item auction, with a decreasing profit difference as the number of bidders and slots they bid for increase (Table 1, Table 3, and Table 5).
- For the cases of random valuation pattern (and again irrespective of the winner determination policy), the terminal operator is better off (except for six instances) using the bundle auction, especially under AWD (Table 1, Table 3, Table 5, and Table 7).
- Mean profit differences between the single and the bundle auction decrease, overall, with the increase in the number of bidders and slots they bid for (Table 1, Table 3, Table 5, and Table 7).

- For the last scenario (Insufficient Supply Scenario, Table 7), the mean profit change between the two auction mechanisms has the same patterns as the rest of the simulations, except for those cases where the minimum number of slot bids is greater than eight. These are cases where demand is greater than the supply, and a different pattern was expected. For these cases, when applying the bundle auction the port operator experiences a decrease in profits between 1.5% and 3.5% compared to the single auction, even for the random valuation pattern (where the port operator was better off using the bundle auction in all other cases).
- For most scenarios, the standard deviation of profit difference close to the mean. The only exception is the base scenario, when using RVP where the number of slots a player can bid for is drawn randomly from a U(X,3X), where X is the minimum number of slots a player can bid for.

## Discussion

In Chapter 2 of this dissertation, we proposed an auction framework for berth-slot leasing in passenger marine terminals (roll-on/roll-off passenger vessels and/or cruise ships). Different variations for the proposed bundle and single auctions, with regards to winner determination, slot valuation, and the number of bidders, were tested and compared under four different simulation scenarios to determine which of the two proposed auction mechanisms is more profitable. The results from the computational experiments show that the proposed bundle auction outperforms the single-item auction when bidders have different valuations for each slot. Additionally, better results are reached when the winner of each round was determined based on their average bid per slot and not on their total bid. The single auction produced significantly higher profits when bidders have similar valuations for each slot (according to a probability distribution). For the cases where demand is higher than supply (insufficient supply), the single auction produces more favorable results. The results from this study can be used by terminal operators, given their knowledge and/or assumptions on slot valuations and demand, to select a winner determination policy and the minimum number of slots they allow players to bid for when designing the auction of their berth capacity to maximize their profits.

## 3. Non-Discrete Berth Length

### Problem Description

In this section, we propose and describe a multi-item, second-price auction framework, which is compared against a single-item, sequential, second-price auction, where the length of berth is a non-discrete variable.

### Methodology

### Single Auction

Under the single-item sequential second-price auction, the port operator auctions each slot sequentially, where the winner for each slot is determined by their highest bid and the price paid to the port operator is equal to the second-highest bid. The sequence with which the slots become available for bidding is important for the outcome of the auction. We assume that the port operator has some knowledge of demand and berth location preference (from experience) and can thus prioritize the auction with slots that they believe are of higher value and will increase the competition amongst the bidders. To start the auction, the port operator makes the first time-slot available for bidding. The bidders submit their bid (in USD/foot) and the length of berth they need (in feet) for that particular time slot if the supply of space can satisfy their demand. After the bidding ends, the winner and the price to be paid are determined. The first-round ends with the berth length awarded being removed from the available length of the slot auctioned. If the remaining length in that slot is less than the minimum allowed length allocation, then the slot in its entirety is removed from the pool of available slots. If the demand of the winner has been satisfied, the winner is removed from the pool of available bidders. The process continues until the demand has been met or the supply has been depleted. Figure 3 presents the steps of the single-item auction used in Chapter 3 of this dissertation.

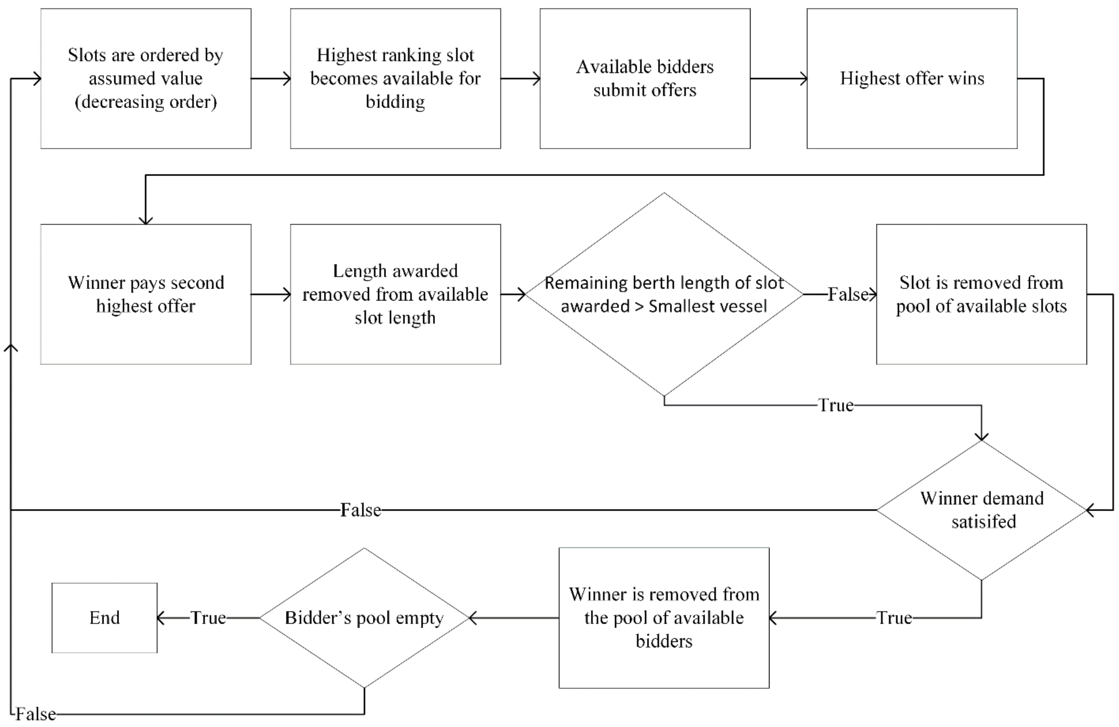


**Figure 3. Single-Item Auction Flowchart for Continuous Berth Length**

## Bundle Auction

The multi-round, second-price, sealed-bid bundle auction proposed in Chapter 3 (as an alternative to the single-item auction) auctions all available slots at the same time, so that each player bids for the slots they need, based on their valuation. Therefore, each bidder's offer includes all the time slots they need and the length of berth for each corresponding time slot as long as the available remaining length in each berth slot is larger than the length of berth requested by the bidder. At each round, the player with the highest bid wins the round and takes all the slots they requested  with their corresponding berth lengths paying the second-highest offer, regardless of what slots the second-highest offer was made for. We evaluate two different winner determination policies (i.e., how the highest bid is estimated), described in more detail later in this section. The winner is removed from the pool of remaining players along with the corresponding lengths of berth from all the time slots they acquired. If the remaining berth length in each time slot that was awarded is less than the minimum allowed length allocation, then the slot is removed from the pool of available slots. In the next round, the remaining bidders resubmit bids for the available slots. The procedure is terminated when all players have received slots or there are no more slots available. At each round, a reserve price is introduced for the slots that have not been awarded, defined as the minimum price that the auctioneer will accept as a winning bid. The reserve price for each slot is calculated based on the mean profit made from all the winning bids in all previous rounds. We adopt a reserve price to address situations where a second-best price for a slot (or bundle of slots) does not exist (i.e., at the last round where only one player remains). Thus, the reserve price, in the way the proposed auction is set up, is only used at the last round of the auction. In that case, the winner will pay a reserve price for the length of timeslots awarded, so that their profit equals the mean profit of all the previous winners. Note that in the proposed auction a reserve price does not alter the behavior of the bidders (i.e., it is still a dominant strategy to bid one’s true valuation), since if the reserve price was higher than the bid, the bidder will not take the slot, and their expected payoff will be zero. Figure 4 presents the steps of the bundle auction.

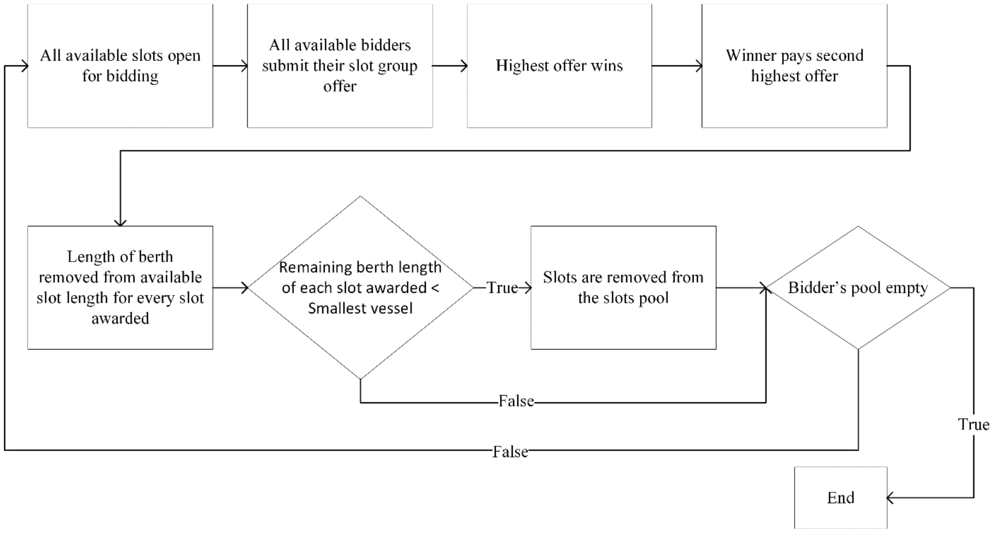


**Figure 4. Bundle Auction Flowchart for Continuous Berth Length**

## Rationale for Second-Price Bundle Auction

Similarly to Chapter 2, a second-price auction is used to encourage irrational players to bid honestly since it ensures that each bidder will end up with non-negative profits for the item(s) they are awarded.

## Auction Assumptions

To apply the proposed auction, the following assumptions are made:

- There is imperfect information, i.e., bidders are unaware of each other's valuation for each slot and of the slots the other players will bid for.
- A possible situation where a bidder bids for more slots than they need to improve their position against the competition is allowed since we are interested in maximizing the port operator's profits and not in an equitable distribution of resources.

## Slot Valuation Pattern

In Chapter 3, in antithesis with Chapter 2, we assumed one slot valuation pattern for each timeslot, that differentiates high demand/volume days such as weekends, to be used in the simulation experiments presented in the next section. More specifically, each bidder has their own valuation for each timeslot which has been assigned randomly. That means that a certain slot might be of high value for one player and of low value for another. This is a more generic way to determine each slot's valuation by every bidder. For high volume days such as weekends, the value of each slot is based on a uniform probability distribution. That is, all bidders have similar valuations for each slot ranging in the highest third of the distribution. This version of slot valuation represents the case of for high competition between the bidders for the most desirable timeslots and, should, increase the port operator's profits since, in each round, the second-highest bid (i.e., price that the winner will pay) would be close to the highest bid (i.e., winner's bid).

## Winner Determination

To determine the winning bid of each round of the proposed auction, we propose two different policies, described next.

### *Winner Determination Policy Based on the Total Bid (TWD)*

Under the TWD policy, the winner is determined based on the highest total bid over all the slots, regardless of how many slots a player has bid for. Let S be the set of all available timeslots, $V(S_i)$ be the valuations of player $i$ per foot for the subset of slots $S_i \subseteq S$, and $F(S_i)$ the length of berth requested by player $i$ for timeslots $S_i$. Assume that players $i$ and $j$ bid for a subset of slots $S_i$ and $S_j$ ($S_i$, $S_j \subseteq S$). Then if $V(S_i)^* F(S_i) \geq V(S_j)^* F(S_j)$ player $i$ will win the bid and be awarded the length of berth they requested for the subset of slots $S_i$. This winner determination policy provides a significant advantage to players that bid for many slots and higher lengths of berth and/or are willing to pay a higher amount. In case of a tie ($V(S_i)* F(S_i)= V(S_j)* F(S_j)$) the winner is the player with the least number of feet of berth requested (i.e., the bidder with the highest average per foot bid). In case of a tie for both the bid ($V(S_i)* F(S_i)= V(S_j)* F(S_j)$) and length of berth ($F(S_i)=F(S_j)$), the winner is chosen randomly.

*Winner Determination Policy Based on Monetary Value per Foot (FWD)*

Under the FWD policy, the winner is determined based on the highest bid per foot of berth length requested (i.e., USD/ft). For example, if bidders $i$ and $j$ offer $V(S_i)* F(S_i)$ and $V(S_j)* F(S_j)$ for slots $S_i$ and $S_j$ respectively, the player with the highest $V(S)$ is the winner. In case of a tie, the winner is chosen based on the length of slots they bid for, but in this case, and in antithesis with TWD, the bidder with the highest number of feet of berth requested wins.

## Numerical Experiments

We compare the proposed multi-round second price sealed-bid bundle auction to the single-item, sequential, second-price auction in this section using the results of a series of numerical tests using Monte Carlo simulation. The winner determination decision problem of multi-item auctions is NP-complete [21] and thus an analytical solution algorithm, to evaluate and compare the proposed auction mechanisms is not feasible, especially for real world problems. We simulated different scenarios by varying assumptions on the number of bidders, minimum vessel size (i.e., length measured in feet), and length of wharf. For every scenario, we simulated 10,000 auctions for each winner determination policy (i.e., TWD and FWD) for both the single and bundle auctions. By varying these parameters for each simulation scenario, we attempt to replicate real life scenarios that may occur during the berth allocation process and correspond to different port sizes (by varying the size of wharf) that serve vessels ranging from small ferries to larger cruise ships (by varying the minimum berth length) experiencing low or high demand (by varying the number of bidders). In all numerical experiments, the number of available timeslots has been set to 360 which roughly represents 2 weeks of scheduling for the port operator and the size of wharf was set to 1,000 ft, 1,500 ft, or 2,000 ft.

Valuations for each slot by each bidder were uniformly distributed between 200 and 1000 $/ft. For days of high demand (e.g., weekends) valuations ranged in the highest third of the above distribution. We considered 15 distinct cases with respect to the number of bidders ranging from 6 to 20. We also considered 4 distinct cases for the minimum length of berth a player can bid for, ranging from 200 ft to 1,000 ft at intervals of 200 ft. Cases of higher minimum length of berth a player can bid for are more suitable for cruise terminals, while cases that allow for smaller vessels correspond better to ferry terminals. A total of 360 unique combinations of winner determination policies, number of players, vessel size, and wharf length were created.

### Results

Next, we present and discuss results from the simulation of the different scenarios. Table 9 through Table 12 summarize the results from the simulation of the single and bundle auctions. The results are presented as the mean percentage change in profits for the port operator between the two different auction mechanisms for each simulation scenario. That is, positive percentage changes illustrate that the port operator experienced higher profits, on average, using the bundle auction. On the other hand, negative percentage changes showcase simulation scenarios where the port operator had higher profits utilizing the single auction. Table 9 shows the terminal operator’s mean profit change for the TWD winner determination policy and Table 11 for the FWD winner determination policy. Table 10 and Table 12 show the standard deviation for each winner determination policy, respectively. The assumption of normality was tested visually through histograms and through the Anderson–Darling test [20]. Figure 5 shows a summary of all the mean profit differences listed in Table 9 and Table 11 so that the patterns are easier to visualize. Results shown in Figure 5 and Table 9 through Table 12 reveal very distinctive patterns that can be summarized as follows:

- Under the TWD policy and irrespective of the values of the other experimental parameters (i.e., number of bidders, minimum berth length requested, and wharf length), the port operator is always better off using the bundle auction (Figure 5**,** Table 9**,** and Table 11)
- Irrespective of the winner determination policy, the port operator is always better off using the bundle auction when the wharf length is 2,000 ft (Figure 5**,** Table 9**,** and Table 11).
- When applying the TWD policy, as the number of bidders and minimum berth length increase, the profit difference between the bundle and the single auction decreases but remains above 50%, 9% and 9% (Figure 5 and Table 9) for the cases of 2000, 1500 and 1000 ft-long wharves, respectively.
- When applying the FWD policy, as the number of bidders increases the profit difference between the bundle and the single auction decreases but when the minimum berth length increases, the profit difference increases (Figure 5 and Table 11).
- Mean profit differences between the bundle and the single auction decrease, overall, with the increase in the number of bidders (Table 9 and Table 11).
- Under the FWD policy, and for a wharf length of 1500 and 1000, the single auction outperforms the bundle auction, especially as the minimum berth length requested decreases (Figure 5 and Table 11).

- For all scenarios, the standard deviation of the mean profit difference is very low for the TWD policy and for the FWD for a wharf length of 2000 ft (Table 10 and Table 12). For the latter policy and for a wharf length of 1500 ft and 1000 ft the standard deviation of the mean profit difference is high, especially for the cases where the bidders' minimum berth request and bidder numbers are low (i.e., 200ft and 400 ft).

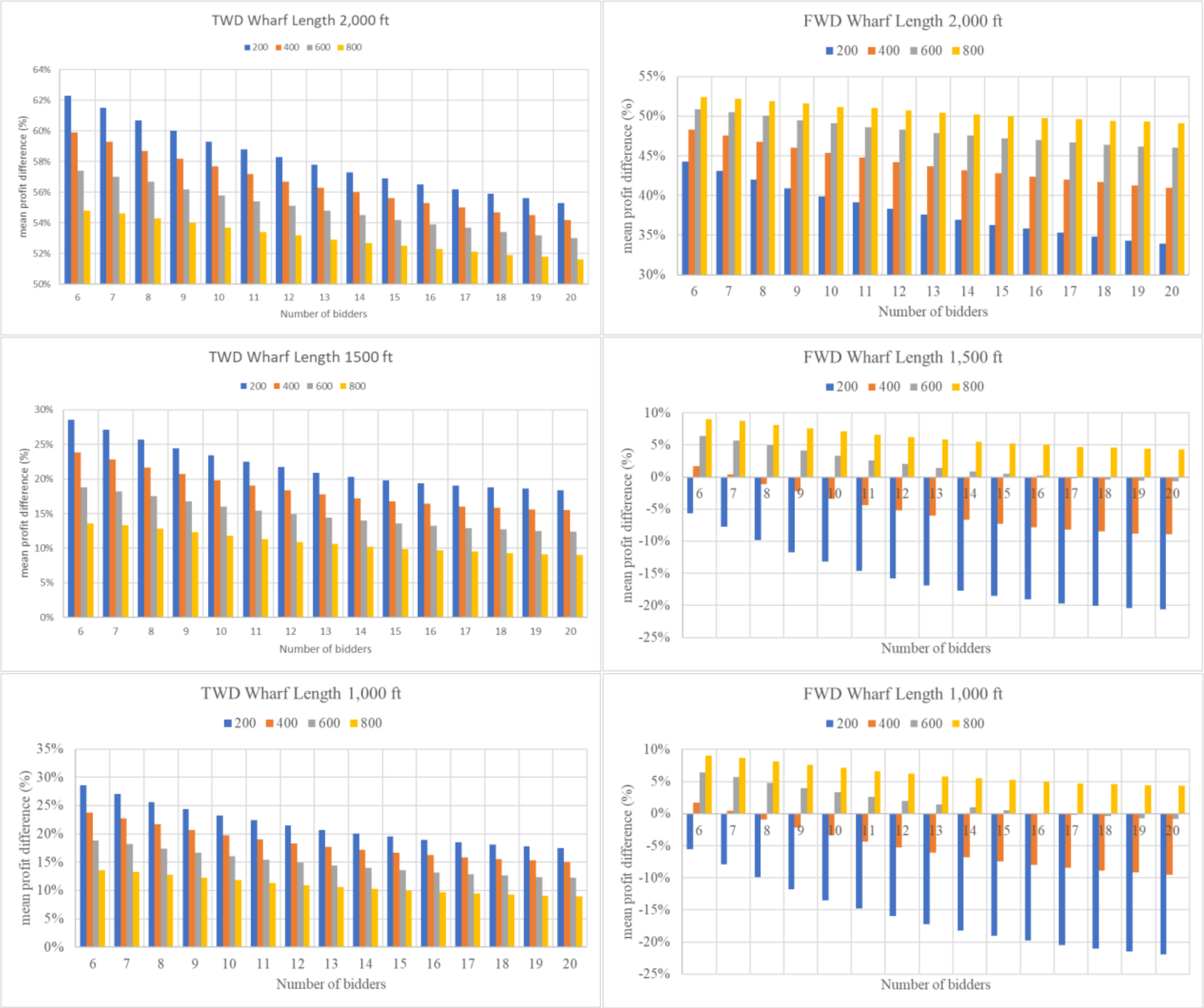


**Figure 5. Mean profit difference (%) by number of bidders, wharf length, winner determination policy and minimum berth length requested by bidder**

## Table 9. Mean Profit Difference (MPD): Bundle vs. Single-Item Auction – TWD

| TWD | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of Bidders | | | | | | | | | | | | | | | |
| Min Berth Length (ft) | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Wharf Length 2,000 ft | | | | | | | | | | | | | | | |
| 200 | 62.3% | 61.5% | 60.7% | 60.0% | 59.3% | 58.8% | 58.3% | 57.8% | 57.3% | 56.9% | 56.5% | 56.2% | 55.9% | 55.6% | 55.3% |
| 400 | 59.9% | 59.3% | 58.7% | 58.2% | 57.7% | 57.2% | 56.7% | 56.3% | 56.0% | 55.6% | 55.3% | 55.0% | 54.7% | 54.5% | 54.2% |
| 600 | 57.4% | 57.0% | 56.7% | 56.2% | 55.8% | 55.4% | 55.1% | 54.8% | 54.5% | 54.2% | 53.9% | 53.7% | 53.4% | 53.2% | 53.0% |
| 800 | 54.8% | 54.6% | 54.3% | 54.0% | 53.7% | 53.4% | 53.2% | 52.9% | 52.7% | 52.5% | 52.3% | 52.1% | 51.9% | 51.8% | 51.6% |
| Wharf Length 1,500 ft | | | | | | | | | | | | | | | |
| 200 | 28.5% | 27.1% | 25.7% | 24.4% | 23.4% | 22.5% | 21.7% | 20.9% | 20.3% | 19.8% | 19.4% | 19.0% | 18.8% | 18.6% | 18.4% |
| 400 | 23.8% | 22.8% | 21.6% | 20.7% | 19.8% | 19.0% | 18.4% | 17.8% | 17.2% | 16.8% | 16.4% | 16.0% | 15.8% | 15.6% | 15.5% |
| 600 | 18.8% | 18.2% | 17.5% | 16.8% | 16.0% | 15.4% | 14.9% | 14.4% | 14.0% | 13.6% | 13.2% | 12.9% | 12.7% | 12.5% | 12.4% |
| 800 | 13.6% | 13.3% | 12.8% | 12.3% | 11.8% | 11.3% | 10.9% | 10.6% | 10.2% | 9.9% | 9.7% | 9.5% | 9.3% | 9.1% | 9.0% |
| Wharf Length 1,000 ft | | | | | | | | | | | | | | | |
| 200 | 28.6% | 27.0% | 25.6% | 24.4% | 23.2% | 22.4% | 21.5% | 20.7% | 20.1% | 19.5% | 18.9% | 18.5% | 18.1% | 17.8% | 17.5% |
| 400 | 23.8% | 22.7% | 21.7% | 20.7% | 19.8% | 19.0% | 18.3% | 17.7% | 17.2% | 16.7% | 16.3% | 15.9% | 15.5% | 15.3% | 15.0% |
| 600 | 18.8% | 18.2% | 17.4% | 16.7% | 16.1% | 15.4% | 14.9% | 14.4% | 14.0% | 13.6% | 13.2% | 12.9% | 12.7% | 12.4% | 12.3% |
| 800 | 13.6% | 13.3% | 12.8% | 12.3% | 11.8% | 11.3% | 10.9% | 10.6% | 10.3% | 10.0% | 9.7% | 9.5% | 9.3% | 9.1% | 9.0% |

## Table 10. MPD Standard Deviation: Bundle vs. Single-Item Auction - TWD

| TWD | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of Bidders | | | | | | | | | | | | | | | |
| Min Berth Length (ft) | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Wharf Length 2,000 ft | | | | | | | | | | | | | | | |
| 200 | 2.6% | 2.2% | 2.0% | 1.7% | 1.6% | 1.5% | 1.4% | 1.3% | 1.2% | 1.1% | 1.1% | 1.0% | 1.0% | 0.9% | 0.9% |
| 400 | 2.3% | 1.9% | 1.7% | 1.5% | 1.4% | 1.3% | 1.2% | 1.1% | 1.1% | 1.0% | 0.9% | 0.9% | 0.9% | 0.8% | 0.8% |
| 600 | 2.1% | 1.7% | 1.5% | 1.4% | 1.2% | 1.1% | 1.1% | 1.0% | 1.0% | 0.9% | 0.9% | 0.8% | 0.8% | 0.8% | 0.7% |
| 800 | 2.0% | 1.6% | 1.4% | 1.3% | 1.1% | 1.0% | 1.0% | 0.9% | 0.9% | 0.8% | 0.8% | 0.7% | 0.7% | 0.7% | 0.7% |
| Wharf Length 1,500 ft | | | | | | | | | | | | | | | |
| 200 | 4.2% | 3.6% | 3.1% | 2.7% | 2.4% | 2.1% | 2.0% | 1.8% | 1.7% | 1.5% | 1.4% | 1.3% | 1.3% | 1.2% | 1.2% |
| 400 | 3.8% | 3.2% | 2.7% | 2.4% | 2.1% | 1.9% | 1.7% | 1.6% | 1.4% | 1.3% | 1.2% | 1.1% | 1.1% | 1.0% | 1.0% |
| 600 | 3.5% | 2.8% | 2.4% | 2.1% | 1.8% | 1.6% | 1.5% | 1.3% | 1.2% | 1.1% | 1.0% | 1.0% | 0.9% | 0.8% | 0.8% |
| 800 | 3.3% | 2.6% | 2.2% | 1.8% | 1.6% | 1.4% | 1.3% | 1.2% | 1.0% | 1.0% | 0.9% | 0.8% | 0.8% | 0.7% | 0.7% |
| Wharf Length 1,000 ft | | | | | | | | | | | | | | | |
| 200 | 4.3% | 3.6% | 3.1% | 2.7% | 2.4% | 2.2% | 2.0% | 1.8% | 1.6% | 1.5% | 1.4% | 1.3% | 1.2% | 1.1% | 1.0% |
| 400 | 3.8% | 3.2% | 2.7% | 2.3% | 2.1% | 1.9% | 1.7% | 1.6% | 1.4% | 1.3% | 1.2% | 1.1% | 1.0% | 1.0% | 0.9% |
| 600 | 3.5% | 2.8% | 2.4% | 2.1% | 1.8% | 1.6% | 1.5% | 1.3% | 1.2% | 1.1% | 1.0% | 1.0% | 0.9% | 0.8% | 0.8% |
| 800 | 3.3% | 2.6% | 2.2% | 1.8% | 1.6% | 1.4% | 1.3% | 1.2% | 1.0% | 1.0% | 0.9% | 0.8% | 0.8% | 0.7% | 0.7% |

## Table 11 Mean Profit Difference (MPD): Bundle vs. Single-Item Auction – FWD

| | FWD | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Bidders | | | | | | | | | | | | | | |
| **Min Berth Length (ft)** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| | **Wharf Length 2,000 ft** | | | | | | | | | | | | | | |
| **200** | 44.3% | 43.1% | 42.0% | 40.9% | 39.9% | 39.1% | 38.3% | 37.6% | 36.9% | 36.3% | 35.8% | 35.3% | 34.8% | 34.3% | 33.9% |
| **400** | 48.3% | 47.6% | 46.8% | 46.0% | 45.4% | 44.8% | 44.2% | 43.7% | 43.2% | 42.8% | 42.4% | 42.0% | 41.7% | 41.3% | 41.0% |
| **600** | 50.9% | 50.5% | 50.1% | 49.5% | 49.1% | 48.6% | 48.3% | 47.9% | 47.6% | 47.2% | 47.0% | 46.7% | 46.4% | 46.2% | 46.0% |
| **800** | 52.4% | 52.2% | 51.9% | 51.6% | 51.2% | 51.0% | 50.7% | 50.4% | 50.2% | 50.0% | 49.8% | 49.6% | 49.4% | 49.3% | 49.1% |
| | **Wharf Length 1,500 ft** | | | | | | | | | | | | | | |
| **200** | -5.7% | -7.7% | -9.8% | -11.7% | -13.2% | -14.6% | -15.8% | -16.9% | -17.7% | -18.5% | -19.1% | -19.7% | -20.1% | -20.4% | -20.6% |
| **400** | 1.7% | 0.4% | -1.1% | -2.2% | -3.4% | -4.4% | -5.2% | -6.0% | -6.7% | -7.3% | -7.8% | -8.2% | -8.5% | -8.8% | -8.9% |
| **600** | 6.4% | 5.7% | 4.9% | 4.1% | 3.3% | 2.6% | 2.0% | 1.4% | 0.9% | 0.5% | 0.2% | -0.2% | -0.4% | -0.6% | -0.7% |
| **800** | 9.0% | 8.7% | 8.1% | 7.6% | 7.1% | 6.6% | 6.2% | 5.8% | 5.5% | 5.2% | 5.0% | 4.7% | 4.6% | 4.4% | 4.3% |
| | **Wharf Length 1,000 ft** | | | | | | | | | | | | | | |
| **200** | -5.5% | -7.9% | -9.9% | -11.8% | -13.5% | -14.8% | -16.0% | -17.2% | -18.2% | -19.0% | -19.8% | -20.5% | -21.0% | -21.5% | -21.9% |
| **400** | 1.7% | 0.4% | -0.9% | -2.2% | -3.4% | -4.4% | -5.3% | -6.1% | -6.8% | -7.4% | -8.0% | -8.4% | -8.9% | -9.2% | -9.5% |
| **600** | 6.4% | 5.7% | 4.8% | 4.0% | 3.3% | 2.6% | 2.0% | 1.4% | 1.0% | 0.5% | 0.1% | -0.2% | -0.4% | -0.7% | -0.8% |
| **800** | 9.0% | 8.7% | 8.1% | 7.6% | 7.1% | 6.6% | 6.2% | 5.8% | 5.5% | 5.2% | 5.0% | 4.7% | 4.6% | 4.4% | 4.3% |

## Table 12 MPD Standard Deviation: Bundle vs. Single-Item Auction - FWD

| | FWD | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of Bidders | | | | | | | | | | | | | | |
| **Min Berth Length (ft)** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| | **Wharf Length 2,000 ft** | | | | | | | | | | | | | | |
| **200** | 3.2% | 2.8% | 2.5% | 2.3% | 2.1% | 1.9% | 1.8% | 1.7% | 1.6% | 1.6% | 1.5% | 1.5% | 1.4% | 1.4% | 1.3% |
| **400** | 2.5% | 2.1% | 1.9% | 1.7% | 1.5% | 1.4% | 1.3% | 1.2% | 1.2% | 1.1% | 1.1% | 1.0% | 1.0% | 1.0% | 0.9% |
| **600** | 2.1% | 1.7% | 1.5% | 1.3% | 1.2% | 1.1% | 1.0% | 1.0% | 0.9% | 0.9% | 0.8% | 0.8% | 0.8% | 0.8% | 0.7% |
| **800** | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | **Wharf Length 1,500 ft** | | | | | | | | | | | | | | |
| **200** | 7.4% | 6.5% | 5.8% | 5.3% | 4.9% | 4.6% | 4.4% | 4.1% | 3.9% | 3.8% | 3.7% | 3.5% | 3.5% | 3.4% | 3.4% |
| **400** | 5.4% | 4.5% | 4.0% | 3.6% | 3.3% | 3.0% | 2.8% | 2.6% | 2.5% | 2.4% | 2.3% | 2.2% | 2.1% | 2.1% | 2.1% |
| **600** | 4.1% | 3.3% | 2.9% | 2.5% | 2.2% | 2.1% | 1.9% | 1.7% | 1.6% | 1.5% | 1.4% | 1.4% | 1.3% | 1.3% | 1.2% |
| **800** | 3.5% | 2.7% | 2.3% | 1.9% | 1.7% | 1.5% | 1.3% | 1.2% | 1.1% | 1.0% | 1.0% | 0.9% | 0.8% | 0.8% | 0.8% |
| | **Wharf Length 1,000 ft** | | | | | | | | | | | | | | |
| **200** | 7.5% | 6.5% | 5.8% | 5.3% | 4.9% | 4.6% | 4.3% | 4.1% | 3.9% | 3.6% | 3.6% | 3.4% | 3.3% | 3.2% | 3.1% |
| **400** | 5.4% | 4.6% | 4.0% | 3.6% | 3.3% | 3.0% | 2.8% | 2.7% | 2.4% | 2.4% | 2.3% | 2.2% | 2.1% | 2.0% | 1.9% |
| **600** | 4.1% | 3.4% | 2.9% | 2.5% | 2.2% | 2.1% | 1.9% | 1.7% | 1.6% | 1.5% | 1.4% | 1.4% | 1.3% | 1.2% | 1.2% |
| **800** | 3.5% | 2.7% | 2.3% | 1.9% | 1.7% | 1.5% | 1.3% | 1.2% | 1.1% | 1.0% | 0.9% | 0.9% | 0.8% | 0.8% | 0.8% |

## Discussion

In Chapter 3, we presented an auction framework for leasing berth slots in passenger marine terminals (roll-on/roll-off passenger ships and/or cruise ships) when space (i.e., berth length) is a non-discrete variable. To ascertain which of the two suggested auction procedures is more lucrative, many iterations of the bundle and single auctions were evaluated and compared in terms of winner determination, the minimum wharf space permitted for bidding, and the number of bidders. To assist port operators in optimizing their revenues, this dissertation focuses on selecting the ideal auction under various conditions.

The results from the computational experiments show that the proposed bundle auction outperforms the single-item auction under both winner determination policies tested herein for the majority of the cases used in the experiments. Additionally, better results (higher profits) are reached when the winner of each round is determined based on their total bid and not on their monetary value per foot requested bid.

# 4. Conclusions and Future Research

In this dissertation, we proposed an auction framework for berth slot leasing in passenger marine terminals (roll-on/roll-off passenger vessels and/or cruise ships). Different variations of the proposed bundle and single auctions, with regards to winner determination, slot valuation, and the number of bidders, were tested and compared under multiple simulation scenarios to determine which of the two proposed auction mechanisms is more profitable. This dissertation was divided into two sections: Chapter 2 where the wharf is discretized by the port operator and the bidders are competing for time slots, and Chapter 3: where berth length was introduced as a continuous variable. Results from the computational experiments in Chapter 2 showed that the proposed bundle auction outperforms the single-item auction when bidders have different valuations for each slot. Additionally, better results were reached when the winner of each round was determined based on their average per slot bid and not on their total bid. The single auction produced significantly higher profits when bidders have similar valuations for each slot (according to a probability distribution). For the cases where demand was higher than the supply (insufficient supply), the single auction produced more favorable results for the port operator.

Different results and distinct patterns were identified in Chapter 3, where the length of berth was introduced as a non-discrete variable. More specifically, Chapter 3 results from the computational experiments show that the proposed bundle auction outperformed the single-item under both winner determination policies tested herein for the majority of the cases used in the experiments. Additionally, better results (higher profits) were reached when the winner of each round was determined based on their total bid and not on their $/foot bid.

The results from this study can be used by terminal operators, given their knowledge and/or assumptions on slot valuations and demand, to select a winner determination policy and the minimum amount of wharf space they allow players to bid for when designing the auction of their berth capacity to maximize their profits.

With the ability to analyze and compare various winner determination procedures and expected payoff methodologies, this work opens several potentials future research areas. In this work, for instance, the wharf is assumed to have been discretized by the terminal operator in terms of time, although berth length is used as a non-discrete variable in Chapter 3. Future research could further introduce a variable berth-time assumption per auction round. Introducing variable berth time into the problem formulation would bring the proposed auction even closer to real-life conditions. It is also possible to consider an optimization technique for choosing the best order of slot availability for bidding. The method may be used for various customer satisfaction and yield strategies/policies of the passenger terminal operations, representing difficulties of congested passenger terminals, servicing either RoPax or cruise boats. Additionally, when the required adjustments have been made, the suggested auction framework can be used in various terminal types or even various transactions relevant to the operation of intermodal freight terminal resource allocation and/or include environmental elements of berth scheduling (e.g., deploying a quantitative approach to the deployment of clean fuels by ships is a pertinent future extension of the research as well.) [22, 23].

The author would like to note that from a managerial perspective (i.e., from the terminal operators or port authority’s perspective) introducing the proposed auction framework as a new policy to allocate the available berth space, could results in companies paying higher prices and could result in a negative reaction. Additionally, allocating berth space through the proposed framework does not consider the overall performance of the quay side of the port (e.g., minimizing total stay time of vessels), although quay performance is usually more important for freight operations (e.g., container terminals) than passenger. Another managerial issue not addressed by the proposed framework is the frequency with which the auction will take place, freedom of information, and how that might affect the bidding strategies once multiple rounds have been completed (e.g., bidders identifying patterns of other bidders and adjusting their bid price, thus deviating from their true valuation). Furthermore, issues of coalition and collusion may be expected. We thus suggest, as future research, incorporating concepts of collusion [24] and co-opetition, within and between the bidders. Accounting for collusion and co-opetition would improve the predictive power of the proposed auction framework. Finally, a future research direction would be to incorporate customer satisfaction (i.e., profit difference of bidders) in the process of choosing the correct auction for each scenario.

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