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Spectrum Auction Policy Design for International Mobile Telecommunications in South Korea: Application of Agent-Based Simulation

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Abstract: Spectrum auctions in international mobile telecommunications (IMT) are a representative method for selling the right to transmit signals within a specific band of electromagnetic waves to communication service providers (CSPs); it is important to design a fair spectrum auction that can benefit both government and auction bidders. The government should reduce the burden of maintenance costs by setting a reasonable initial price and selling it to bidders at the highest price they can afford. However, due to the complex auction rules and decision-making process, not many studies has been conducted on how to select an appropriate initial price for the auction. This study aims at introducing a novel simulation modeling approach to develop a spectrum auction policy for international mobile telecommunications (IMT) using agent-based simulation (ABS), which involves three telecommunications service provider types (i.e., the Aggressive bidder, the Moderate bidder, and the Conservative bidder) and the auction environment of IMT in South Korea. In particular, the proposed approach adopts the exponential utility theory to model the behavior of auction bidders and identify the optimal initial bid price. The devised ABS model is calibrated to the IMT spectrum auction conducted in 2018 in South Korea, and the best initial pricing policy identified (i.e., $85.24 million per spectrum block) regarding a sustainable market environment for existing service providers (i.e., 10 blocks for the Aggressive bidder, 10 blocks for the Moderate bidder, and 8 blocks for the Conservative bidder). The proposed approach will be beneficial to both government agencies and auction bidders under fair competition in the IMT market.

Keywords: agent-based simulation; spectrum auction; international mobile telecommunications; clock auction; exponential utility theory

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1. Introduction

As the need for information and communication technologies (ICT) increases, the spectrum auction of international mobile telecommunications (IMT) becomes more significant. The spectrum auction is a common way of selling the rights of signal transmission within a specific band of an electromagnetic section to telecommunication service providers [1]. For decades, most countries, including Australia, Hong Kong, India, Indonesia, Malaysia, New Zealand, Singapore, and South Korea, have adopted the spectrum auction to allocate their IMT spectrum blocks to telecommunication service providers [2–6].

This is because the auction is recognized as a fair way to allocate the limited IMT spectrum blocks to the service providers. Its operation is transparent and open to all participants, so that the entire process can be audited and verified by a third-party organization [7]. Moreover, the auction is beneficial to the government and the public. Once the auction starts, it can only be stopped when the bidding has stopped. This implies that the government can receive an offer with the maximum value from a bidder (i.e., a service provider). If the auction is fairly designed under mutual agreement between all participants, the monetary benefit can be utilized to enhance the quality of public life [8]. Although the spectrum auction is a rare event, as bidders purchase the spectrum at a high cost and are granted the right to use it for 5 or 10 years, it is an important issue because the benefit of the spectrum auction can reduce the national tax and be used for the research and development budget in the ICT field.

On the other hand, the outcomes of the auction can be unsatisfactory. An auction is inappropriate for certain public spectrum blocks, such as emergency service and defense, which require protection and cyber security from harmful interference [9]. Considering that those public spectrum blocks are operated by tax, it is challenging to both increase the price of public spectrum use and reserve a wide range of spectrum blocks [8]. Moreover, according to auction styles, it is possible to have side effects that include bid sniping and an exposure problem (see Section 2.1 for more detail). Under the intensively competitive environment between bidders, it is possible that the contract price is far too high. In the spectrum auction of 700 MHz in 2008 in the U.S., the auction revenue was $19,592 million, which was much higher than the $7 billion expected by analysts [10]. To avoid potential problems, there are many studies of the methodologies of the spectrum auction, and the major methodologies are addressed in Section 2.1. Recently, a combinatorial clock auction (CCA) has been considered the best approach to avoid problems, such as bid sniping, as well as an exposure problem [11]. It is for this reason that South Korea adopted the clock auction (CA) with an ascending rule in 2018.

In addition to the aforementioned, studies have been mainly conducted on how to design a fair auction for the recent issue of allocating 6G spectrum as well as 5G. For example, a method for designing dynamic spectrum sharing for 6G to accommodate the needs of various users was proposed by designing the auction process using game theory [12]. For an effective 5G auction in France, the partially observable Markov decision process (POMDP) was utilized to avoid solutions of a dynamic programming equation in the space of beliefs [13]. A quality of service (QoS)-aware priority-based spectrum management scheme [14] was devised to allocate spectrums in 5G and 6G to vertical sector players (VSPs) using a modified Vickrey–Clarke–Groves (VCG) auction mechanism to ensure minimum required bit rates for VSPs. Although these studies have been conducted with various methodologies to maximize the effectiveness of spectrum auctions, simulation-based decision-making methodologies have not yet been considered. Instead of the aforementioned mathematical model-centric approaches [2], this study aims at identifying the best initial price of the auction using the simulation-based optimization approach. To this end, this study adopts agent-based simulation (ABS), which enables the behavior of telecommunications companies (or bidders) in the IMT spectrum auction to be mimicked. ABS is a well-known modeling and simulation (M&S) technique to evaluate the performance of a new policy or system based on the responses of multiple agents, who have their own decision-making processes under a dynamic environment [15,16]. The proposed ABS consists of three major agent types: (1) the Aggressive bidder, (2) the Moderate bidder, and (3) the Conservative bidder. These agents are classified based on the competitive advantages (e.g., buying power) of the auction buyers (see Section 2.3 for more detail). The proposed simulation approach is implemented using AnyLogic 8.6.0 simulation software

and calibrated with data of the IMT spectrum auction in South Korea. The differences between the proposed approach and existing studies are as follows.

- It is the first method to implement the IMT spectrum auction process under the CA based on agent-based simulation. Unlike the macroscopic and top–down approaches of existing mathematical models, the decision-making process of individual agents, such as individual auction participants, is implemented, and a bottom–up approach is proposed by modeling the interrelationships between auction components.
- Exponential utility is used to model the decision-making behavior of auction participants. Exponential utility is a well-known theory that describes the economic choice process of individuals. In conventional mathematical economics, it is expressed in a macroscopic way for predicting the decision-making results of a group (top–down approach), but in this study, it is used as a theory that describes the choice process of individual bidders (bottom–up approach).
- The proposed approach is the first to apply the simulation-based optimization method to an IMT spectrum auction and analyze the optimal auction initial price; the proposed methodology is calibrated using actual IMT auction data from 2018 in Korea.

As a result, this novel approach will contribute to the precise design of the clock auction (CA) with an ascending rule in the IMT spectrum, and it will be beneficial to the government agency that has to identify the appropriate value of the spectrum without causing harmful influence on fair competition in the IMT market for the public, as well as for existing service providers. Moreover, it will extend the applications of ABS in telecommunications and economics.

The organization of the paper is as follows: Section 2 explains major approaches to the spectrum auction, and the price selection behavior of bidders in the auction. The ABS modeling approach in AnyLogic 8.5.0 and identification model of the best initial price of the auction are also introduced. Section 3 demonstrates the proposed approach with data of the IMT spectrum auction in South Korea in 2018. Section 4 discusses the theoretical and managerial implications of the proposed approach. Section 5 concludes this study and addresses future work.

2. Materials and Methods

2.1. Spectrum Auction

As mentioned in the Introduction, the spectrum auction has become popular in many countries, including Australia, Hong Kong, India, Indonesia, Malaysia, New Zealand, Singapore, and South Korea, to sell the rights of providing telecommunication services via specific bands of the electromagnetic spectrum [2–6]. For example, Australia adopted the spectrum auction for IMT spectrum blocks involving 700 to 2600 MHz since 2013 [3]. Similarly, Hong Kong also utilized the auction system for wireless broadband in 2009 and 2011 [17]. The Ministry of Science and Information and Communications Technology (MSIT) in South Korea has sold IMT spectrum blocks involving 3.5 and 28 GHz since 2011 [18].

There are four types of spectrum auctions, including the sealed bid auction, the simultaneous multiple round ascending auction (SMRA), the combinatorial clock auction (CCA), and the descending price combinatorial clock auction (DCCA). In a traditional sealed bid auction, all bidders submit their sealed bids to an auctioneer at the same time, and the highest bid is selected as the winner [19].

The simultaneous ascending auction (SAA) was devised from the English auction that auctions multiple items in a single round, and the SAA repeats over multiple rounds in the SMRA [20]. Although the SMRA has been adopted more than 80 times since 1994 as a spectrum auction, there exists a major problem, known as bid sniping, in which a bidder

waits until the end of each round and significantly increases either their bidding price or quantity [21]. Because this misbehavior disturbs the efficiency of the auction, the Federal Communications Commission (FCC) in the U.S. sets the regulation that, during an auction, each bidder should maintain a similar behavior tendency. In other words, a bidder cannot significantly increase their bidding price, as well as quantity [22]. Also, there exists the exposure problem that bidders reduce their bids to avoid losses caused from not winning all of the spectrum blocks [2].

The CCA was devised to avoid problems associated with the SMRA by auctioning generic spectrum blocks. It consists of the clock phase expressing demand for the spectrum blocks, and one additional sealed-bid phase assigning a specific price and spectrum blocks to the bidders [11]. In this auction, the latest bid price is provided to all bidders like a "clock", and the generic spectrum is auctioned to bidders first. Because a bidder only bids for a quantity of spectrum, it is known as an appropriate approach when technologies used in a certain spectrum band are undecided [23]. The bidder can choose a technology after a specific spectrum band is allocated at the second stage [24]. In addition, similar to the CCA, the DCCA bids on packages of generic spectrum blocks, but it reduces bids over multiple iterations [25].

Similar to the CCA, South Korea adopted the CA with an ascending rule for the IMT auction in 2018. This consisted of seven processes [26]: (1) collecting applications, (2) scheduling the auction, (3) conducting the auction, (4) allocating spectrum blocks, (5) payment, (6) cancellation, and (7) documentation. The IMT auction requires a big budget (e.g., the total price of the IMT auction for 28 generic blocks at 3.5 GHz in 2018 in South Korea was $3201.67 million), so that not all telecommunications companies can attend the auction. Thus, the government must understand the demand of the IMT market by collecting applications from major companies. Once there are multiple bidders, the government enables the auction schedule, conduct, and allocation. After the auction, all bidders have to pay their fee to the government. During the cancellation stage, a company that cannot pay the fee loses its right to use the IMT spectrum blocks, and then other companies are enabled to achieve the right to use the allocated IMT spectrum blocks for their business.

2.2. Behavior in Vickrey-Nearest-Core Pricing

In the CCA (or the CA with an ascending rule), prices are determined according to the Vickrey-nearest core (VNC) pricing, which is known as the ideal pricing rule for truthful bidding [22]. This is because a winner pays the social opportunity cost at each round, so that the rule can maximize the total social opportunity cost at the final round [27]. Harsha et al. [28] addressed that a bidder only shifts to relatively cheaper packages (or blocks). This behavior can be illustrated in Equation (1).

$$q_{t'}(p_{t'} - p_t) \leq q_t(p_{t'} - p_t) \tag{1}$$

where q_t is a package at time t; q_t is a suggested price at time t; and $t' > t$. Moreover, Equation (2) represents a condition of revised package bid $b(q_t)$ at time t.

$$b(q) \leq b(q_t) + (q - q_t)p_t \tag{2}$$

This implies that all supplementary bids (i.e., $b(q)$) should be less profitable than $b(q_t)$. Each bid for q_t is improved in the supplementary round. This is known as the

revealed preference rule, in which all bidders try to select the most profitable package in the CCA [25]. Equation (2) can be rewritten as Equation (3) with the final round (f) [22].

$$b(q) \leq b\left(q_f\right) + \left(q - q_f\right)p_f \tag{3}$$

From Equation (3), two propositions can be derived as follows: (1) the final assignment of spectrum blocks is identical to the clock assignment when there is no excess supply; (2) the winning price should have its maximum value at the final round when there exists excess supply. This is because in the auction, p_t increases over time t (or multiple rounds).

The question then is how a bidder increases his/her bidding price over multiple rounds. In fact, the behavior of four bidders in the German 4G spectrum auction in 2010 can answer this question. In 2010, the market shares of T-Mobile, Vodafone, O_2, and E-Plus were 34%, 30%, 19%, and 17%, respectively [29]. During the auction, each company acted differently based on its bargaining power. For example, E-Plus (i.e., the weakest bidder in terms of the market share) reduced its demand on spectrum blocks at 800 MHz, and O_2 took over E-Plus from KPN with €8.55 billion in 2013 after the auction. On the other hand, the three other bidders tried to buy more blocks for their business (see [29] for more detail).

The bargaining power that is heavily influenced by the market share of a company affects the results of the auction. Similar to the German 4G spectrum auction, in the 3G spectrum auction in the UK in 2000, only five companies, TIW, Vodafone, BT3G, One2One, and Orange, could win in auctions for five licenses over 150 rounds from 6 March 2000 to 27 April 2000 [30]. The market shares of Vodafone, BT3G (or BT Cellnet), Orange, and One2One were 37.3%, 30.1%, 17.2%, and 15.4%, respectively (N. M. Rothschild & Sons, 1999). TIW is one of another nine overseas firms that joined in the auction. As a result, the company that has the most bargaining power is likely to win the auction. Even though a big company may not win the auction, it can take other companies with spectrum licenses (see the German 4G spectrum auction). The budget constraint cannot be ignored in the auction, because of the high selling price. Moreover, according to [30], the bidding in early rounds is arbitrary. Although there was significant increase in the auction price during the latter rounds, both auctions in Germany and the UK followed the SMRA (or SAA). This implies that the bid sniping issue in both auctions can be resolved by adopting the CCA [22].

In fact, similar to the SMRA (or SAA), bidders in the CCA have their preferences on certain spectrum blocks for the success of their business. Under the budget constraint, they try to maximize their utility in the future. If a bidding price is discounted, a bidder tries to buy more spectrum blocks to achieve a competitive advantage [31]. Janssen and Kasberger [11] adopted the quadratic utility model to illustrate the behavior of bidders, and differentiated the weakest bidder based on the budget constraint in the auction. Equation (4) represents the quadratic utility model [11].

$$U(x, \theta_i) = \theta_i x - (\sigma/2)x^2 \tag{4}$$

where $\underline{\theta} \geq \theta > 0$, and $x \in [0, 1]$. Bidder type θ_i acquires a share of x in the auction, and σ is a parameter to regulate the variance of θ. In other words, by conditioning on $\underline{\theta} \geq \sigma$, the utility function enables x to keep increasing for all types of θ_i. The most significant issue is that each bidder has its preference on the decision-making (or selection of price and number of spectrum blocks), and the preference forms utility to a bidder. Thus, this study will adopt the utility theory in ABS to illustrate the behavior of a bidder in the CA with an ascending rule. As Munro and Rassenti [25] showed the capability of ABS in the spectrum auction, this study will adopt ABS. However, this study will focus more on the development of ABS regarding the decision-making behavior of auction bidder agents. Section 2.3 addresses the proposed approach in detail.

2.3. Agent-Based Simulation for the Design of a Spectrum Auction Policy

The proposed ABS has been developed under the CA environment. In particular, for precise simulation modeling, the CA with an ascending rule used for the IMT auction in 2018 in South Korea is considered. The goal of the auction was to allocate 28 generic blocks at 3.5 GHz bandwidth (i.e., 3420–3700 MHz) to three major telecommunication companies (i.e., companies A, B, and C) in South Korea (LG Uplus, n.d.; SK Telecom, n.d.; KT, n.d.). The total bandwidth of 280 MHz is divided into 28 generic blocks of 10 MHz. Each company is not allowed to buy more than 100 MHz according to the monopoly regulations enacted by the Korean government. Once the spectrum blocks are allocated to three companies, they can use them from 1 December 2018 to 30 November 2028 (i.e., 10 years). The minimum price of the auction (i.e., starting price) is $2348.76 million for 28 generic blocks [26]. Figure 1 reveals a conceptual model of the proposed ABS approach for the CA with an ascending rule.

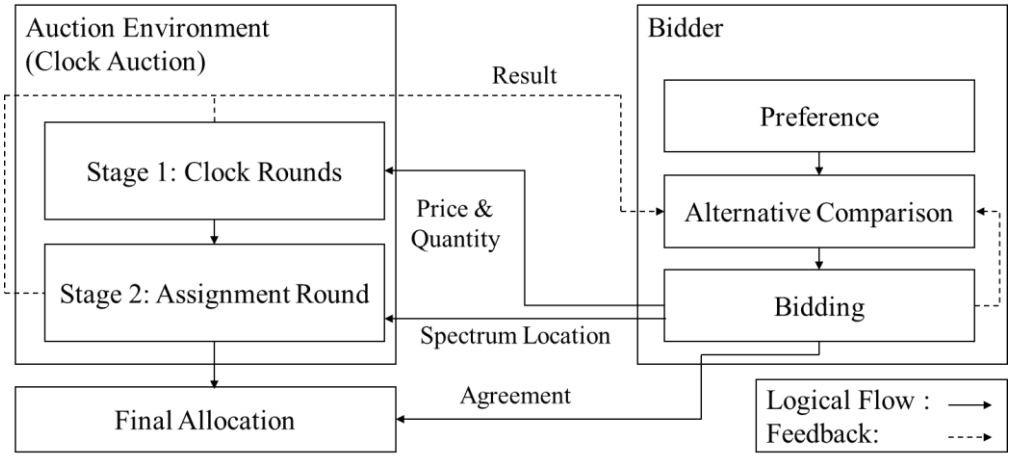


Figure 1. Conceptual model of the proposed agent-based simulation approach for the clock auction.

The ABS consists of two major elements: (1) the auction environment, and (2) a bidder agent. The auction environment is given by the government agency (e.g., the Ministry of Science and Information and Communications Technology in South Korea), which determines the auction rules to fairly allocate the existing spectrum blocks to bidders. The bidder agents mimic the behavior of telecommunication companies that attend the spectrum auction. Significant outputs of the proposed simulation model include the initial price (or the minimum price at the first round), the number of rounds required to have a converged price, the final allocation, the price increment at each round, and the bidding trends. Although the model is developed based on the spectrum auction in South Korea, it can be applied to any spectrum auction using the CA, because the auction process is a de facto standard (see Section 2.2). Sections 2.3.1 and 2.3.2 detail the two major elements in ABS.

2.3.1. Bidder Agents

Figure 2 represents the decision-making process model of the auction bidder agents in the agent-based simulation. In Figure 2, the decision-making process of each agent consists of two states, namely an Idle state and a Decision state. In the Idle state, a bidder agent is preparing for the next round of an auction regarding its investment preference, which is influenced by budget (Budget). As mentioned in Section 2.2, the budget constraint is the most significant factor for the decision-making of a bidder [11]. In this stage, the agent evaluates alternatives in terms of the price increment and the number of spectrum blocks.

At the Decision state, the agent offer is a bid involving the auction price (Price) and the demand for spectrum blocks (NumOfBlocks).

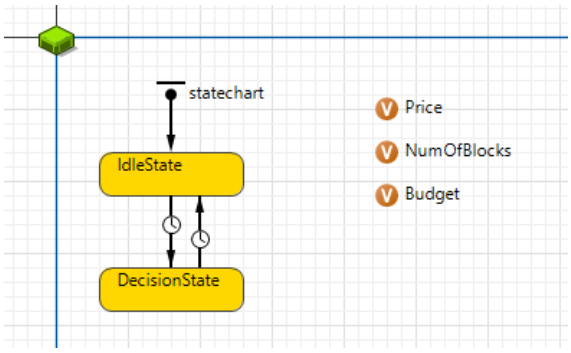


Figure 2. The decision-making process of auction bidder agents.

To model the decision-making behavior of an agent, this study adopts the exponential utility theory, which is widely adopted in the choice behavior modeling of a corporation or an individual [15]. This is because, as the price increases, the choice probability of a human (or a company) exponentially decreases. Thus, the acceptance rate at a certain suggested price of each agent follows Equation (5). Note that the government agency determines the suggested price based on the rule of Vickrey-nearest core pricing (see Section 2.2).

$$y = \lambda exp\left(-\lambda\left(p_{suggested}/b\right)\right) \tag{5}$$

where $p_{suggested}$ is the suggested (or offered) price at each round, and b is the available (or investment) budget of a bidder agent. λ is the price sensitivity of each agent where $0 < \lambda < 1$, and it is affected by the investment preference. Under the given λ and b, as the suggested price ($p_{suggested}$) increases, the choice probability (y) decreases, due to the economic burden on the bidder. This implies that, as the suggested price increases, the demand in terms of the number of spectrum blocks should be reduced, because the total price of each bid is computed by multiplying the suggested price by the number of spectrum blocks.

Suppose that L is the upper limit of demand referring to the maximum number of spectrum blocks bought by a single bidder. Then, Equation (6) represents the actual demand of spectrum blocks, which is influenced by the price sensitivity of each agent on the upper limit of demand on the spectrum blocks (i.e., L/λ).

$$m = \left(\frac{L}{\lambda}\right)\lambda exp\left(-\lambda\left(p_{suggested}/b\right)\right) = L{\cdot}exp\left(-\lambda\left(p_{suggested}/b\right)\right) \tag{6}$$

Eventually, Equation (6) enables the choice behavior of a bidder agent who tends to buy more spectrum blocks with low price sensitivity (λ) or at the cheap suggested price ($p_{suggested}$) to be modelled. The proposed ABS consists of three major agent types: (1) the Aggressive bidder (Type 1), (2) the Moderate bidder (Type 2), and (3) the Conservative bidder (Type 3). The Aggressive bidder is the most competitive company in terms of budget for the spectrum auction. To be more competitive by taking spectrum usage right, it has sufficient budget for the auction. On the other hand, the Conservative bidder is considered the least competitive company in terms of the auction budget. The Moderate bidder is between the Aggressive bidder and Conservative bidder in terms of the auction budget. It tends to maintain its current market share. The difference in decision-making between these three types of agents is determined by the parameter λ which is the price sensitivity of

each agent. Figure 3 reveals the pseudo code to compute m based on the three parameters (i.e., λ, $p_{suggested}$, and b) addressed in Equation (6).

```
1:  START
2:  CALL λ, p_suggested, and b
3:  COMPUTE choice probability y
4:  COMPUTE demand of spectrum blocks m
5:  RETURN m
6:  END
```

Figure 3. Pseudo code of the demand generation function.

Figure 4 depicts how the number of spectrum blocks can vary under three different price sensitivity parameters (i.e., 0.01, 0.07, and 0.22). Notice that the three different values of λ that can represent the decision-making differences of the three agent types are obtained by using the calibration model presented in Section 2.3.3. Since $p_{suggested}$ and b for each agent type can be obtained and inferred from historical data, such as sales and previous auction records, λ can be found from the two given parameter values.

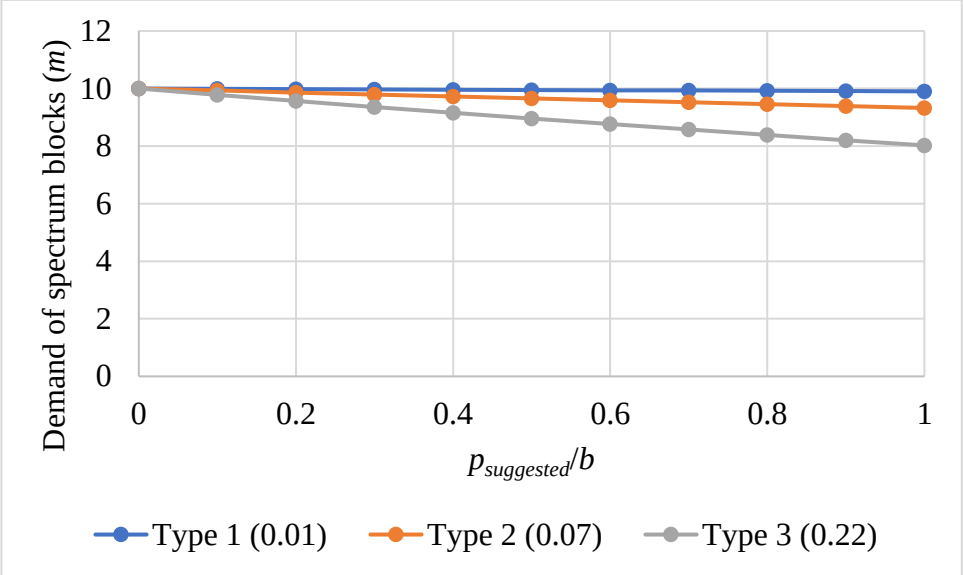


Figure 4. Demand (m) change under three price sensitivity parameters.

In Figure 4, although as the value of $p_{suggested}/b$ increases, the demand (i.e., the number of spectrum blocks) decreases in all three cases, the case with parameter of 0.22 can make the demand rapidly change under different values of $p_{suggested}/b$. The change ratios of the three cases (i.e., 0.01, 0.07, and 0.22) from 0 to 1 of $p_{suggested}/b$ are 0.01, 0.07, and 0.20, respectively. This study assumes that the Aggressive bidder agent is less sensitive to the values of $p_{suggested}/b$, so it has a low value of λ. This is because it has sufficient budget to attend the auction and competitiveness in the market. Due to similar reasons, the Conservative bidder agent is more sensitive to the values of $p_{suggested}/b$ (i.e., a high value of λ) than are the other two types of agents.

2.3.2. Auction Environment Modeling

The three agent types addressed in Section 2.3.1 participate in a spectrum auction in the simulation model consisting of multiple rounds. At each round, the model sends the information of the suggested price to all agents. According to the rule of CA, the suggested price cannot exceed an upper limit on the ratio of the price increment (i.e., SuggestedPriceRate). To consider the uncertainty involved in the suggested price, uniform distribution is used to determine the suggested price, which is between the selected price ($p_{selected}$) at the former round and the maximum price, considering the upper limit on a ratio of the price increment at the current round. For example, when the SuggestedPriceRate is 1% and the selected price at the former round is \$2348.76 million, the suggested price at the current round is randomly selected from any value in the range \$2348.76−2372.25 million. Note that the price choice in early rounds is arbitrary [30].

In addition, after the first round, each bidder agent can offer two alternative prices (i.e., two bids). These two prices should be higher than the selected price at the former round, and lower than the suggested price at the current round [26]. Similar to the suggested price selection, uniform distribution is used to determine the two prices for each agent. However, the demand of spectrum blocks (m) is computed by Equation (3) under the two different prices. In this case, two bidding prices are used, instead of $p_{suggested}$.

Once all bids involving values of m are generated, the simulation model considers the bids in ascending order. However, according to the rule of CA addressed in Section 2.1, the model only considers the case in which the total value of m equals the number of the supplied spectrum blocks (M). If there is no such case, the bidding price and demand of spectrum blocks are determined by the rule addressed in Section 2.1. This complex calculation is modeled by the event module in AnyLogic 8.5.0. Figure 5 provides an overview of the developed simulation model.

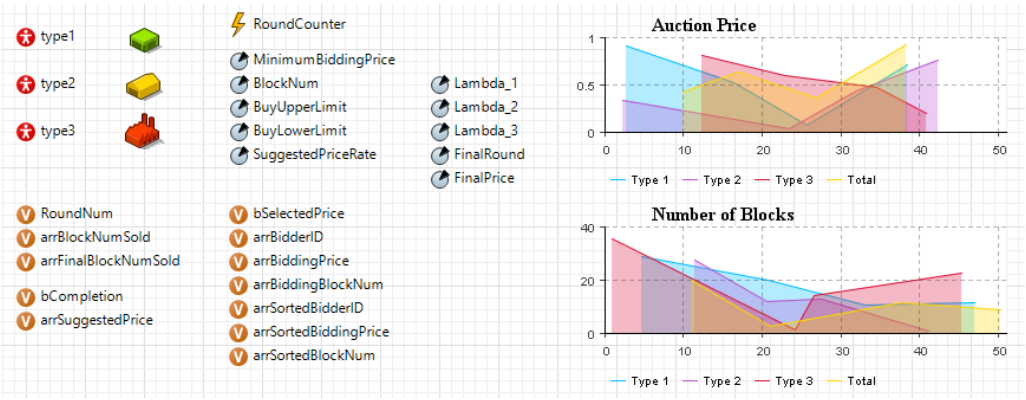


Figure 5. An overview of the developed simulation model in AnyLogic 8.5.0.

Figure 5 shows that the developed simulation environment includes multiple variables and parameters of ABS, while Table 1 addresses the major variables to illustrate the spectrum auction environment. In particular, since the CA requires multiple rounds to compare the current price (or suggested price) with the selected price, multiple variables are required. Also, all suggested prices should be sorted in ascending order for the selection of the minimum price (p_{min}). This is because the price should satisfy all bidders situations. If the maximum price is selected from the suggested prices, only some of the bidders with sufficient budget (e.g., the Aggressive bidder and the Moderate bidder) can buy the spectrum blocks. Note that the goal of the auction held by a government agency is to identify an appropriate value for the spectrum by allocating all blocks to bidders, without causing any harmful impact on a monopolistic market, as well as the public (i.e., the users of the IMT services). Section 3.1 will address additional parameters.

Table 1. Major variables used in the simulation model.

Variable	Description
RoundNum	Round indicator
bCompletion	Completion status of the auction (false: not finished; true: finished)
bSelectedPrice	The existence of selected price (false: not selected; true: selected)
arrBlockNumSold	Total number of spectrum blocks demanded by bidder agents over rounds
arrFinalBlockNumSold	Total number of spectrum blocks sold to bidder agents over rounds
arrSuggestedPrice	Suggested price over rounds
arrBiddingBidderID	ID of a bidder agent
arrBiddingPrice	A list of bidding prices
arrBiddingBlockNum	A list of numbers of spectrum blocks demanded by agents
arrSortedBidderID	Sorted IDs of bidder agents in ascending order
arrSortedBiddingPrice	Sorted prices of bidder agents in ascending order
arrSortedBlockNum	Sorted number of spectrum blocks of bidder agents in ascending order

Figure 6 shows the selection logic from multiple bids involving price and demand (i.e., number of spectrum blocks). Once each agent offers its bid, the ABS collects the bids, and selects the bidding price (i.e., selected price, $p_{selected}$) at each round. The first round uses the minimum price suggested by the government agent (i.e., p_{min}). After that, the suggested price ($p_{suggest}$) is compared to all bid prices given by the agents. If the total demand equals the total number of spectrum blocks for sale, the function returns the selected bidding price ($p_{selected}$). Otherwise, the ABS computes a new suggested price for the next round. The CA continues until it finds a price where the total demand equals the total number of spectrum blocks for sale.

```
START
CALL p_min, p_suggest, and lists of bidding prices, IDs, and demands
If RoundNum <1
    RETURN p_min
ELSE
    SORT all bidding prices, IDs, and demands in ascending order
    For the list of sorted bids
        IF the total demand equals to the total number of spectrum blocks for sale THEN
            RETURN p_selected
        ELSE
    NEXT
```

Figure 6. Pseudo code of the selected price generation function.

2.3.3. Calibration Model

The calibration model is used to identify parameter λ referring to the price sensitivity of an agent. Because the price sensitivity can vary according to market competitiveness (or budget in the auction), this parameter should be calibrated from historical data (i.e., auction results). Although this paper only introduces three types of agents in terms of competitiveness, the auction can include more than three bidders. As an example, there were

13 bidders at the 3G spectrum auction in the UK in 2000 [30]. To generalize the proposed model, let $\lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_n\}$, where n is the number of bidders; $0 < \lambda_i < 1$; and $\lambda_i \neq \lambda_j$ for $\forall i, j, 1 \leq i \leq n, 1 \leq j \leq n$. We would like to identify λ with the minimum estimation error in terms of the coefficient of determination (R^2). Equation (7) is devised from the equation of R^2.

$$Min\ Z = 1 - \sum_{i \in \mathbf{I}} \left(d_i - \hat{d}_i(\lambda) \right) / \sum_{i \in \mathbf{I}} \left(d_i - \overline{d} \right) \quad (7)$$

Subject to the following:

$$M \left| n_{finalround} - \hat{n}_{finalround} \right| \leq \delta \quad (8)$$

$$|m_i - \hat{m}_i| = \varepsilon \quad \text{for } \forall i \in \mathbf{I} \quad (9)$$

$$\sum_{i \in \mathbf{I}} \hat{m}_i = M \quad (10)$$

In Equation (7), $\hat{d}_i(\lambda)$ is the final bidding price estimated by the simulation model under the given λ, and $\overline{d}$ is an average from the historical data of d_i. Equation (8) is a constraint computing the difference between the number of rounds with the final decision ($n_{finalround}$), and the estimated number of rounds with the final decision ($\hat{n}_{finalround}$). Equation (9) refers to the difference between the number of spectrum blocks sold to bidder i (m_i), and the estimated number of spectrum blocks sold to bidder i ($\hat{m}_i$). Equation (10) regulates that the total number of spectrum blocks sold to bidders equals the number of the supplied spectrum blocks (M).

2.3.4. Identification Model of the Minimum Bidding Price

The calibrated model can be used to identify the best minimum bidding price (or initial bidding price) at the spectrum auction. Let $p_{min,1}$ be the minimum total bidding price at the first round, and $\hat{p}_{final}(\bullet)$ be the final bidding price estimated by the simulation model. Equation (11) represents the optimization model for the identification process.

$$Max\ W = \hat{p}_{final}(p_{min,1}) \quad (11)$$

Subject to the following:

$$\tau_{min} \leq p_{min,1} \leq \tau_{max} \quad (12)$$

$$\varphi_{min} \leq \hat{n}_{finalround} \leq \varphi_{max} \quad (13)$$

Equation (12) is a constraint on the range of $p_{min,1}$. τ_{min} and τ_{max} are parameters regulating the lower and upper bounds of $p_{min,1}$. The simulated round with the final decision ($\hat{n}_{finalround}$) is regulated by Equation (13), where $1 \leq \varphi_{min} \leq \varphi_{max}$. Note that the lower bound of $\hat{n}_{finalround}$ (i.e., φ_{min}) should be greater than or equal to 1, because the auction requires at least one bidding round. Since all other constraints are involved in ABS (see Sections 3.1 and 3.2), the final bidding price can be accurately estimated under various values of $p_{min,1}$ with two constraints in Equations (12) and (13).

3. Results

3.1. Scenario

In this study, we investigate the change in behavior of bidders under different initial prices. According to the Ministry of Science and Information and Communications Technology [26], the minimum price of the auction (i.e., starting price) was $2348.76 million for 28 generic blocks (see Section 2.3 more information). The annual revenues of Company A, Company B, and Company C in the mobile telecommunication business in 2017 were $9613.95, $5841.28, and $4928.82 million, respectively. Thus, the minimum bid-

ding price was approximately 11.52% of the total annual revenue of the three companies (i.e., $20,384.06 million). Considering that the annual profit of each company in the IMT market was about 7% of its annual revenue (LG Uplus, n.d.; SK Telecom, n.d.; KT, n.d.), the minimum bidding price could be a burden to all three companies. This implies that each bidder should make its own bidding strategy to maximize its profit in the future.

This study adopts three cases for the investigation of the bidders' behavior under different initial prices: (1) low price (5% of total annual revenue), (2) high price (20% of total annual revenue), and (3) the optimal price. The optimal price was achieved from the simulation-based approach addressed in Section 2.3.4. Table 2 represents the input and output parameters used in the experiments. In particular, the price sensitivity parameters of the three companies (i.e., λ_1, λ_2, and λ_3) are calibrated in Section 3.2 with the historical data of the IMT spectrum auction in 2018 in South Korea, before we conduct experiments. After all input parameters were identified, each scenario was evaluated with 50 replications to achieve statistically reliable results. Simulation time was used as an indicator of an auction round, so that the time horizon of each simulation run was 50 rounds.

Table 2. Simulation input and output parameters.

Parameter	Description	Value
MinBiddingPrice	Lower limit of total bidding price	$2348.76 million
BlockNum	Total number of spectrum blocks for sale	28 blocks
BuyUpperLimit	Purchasing upper limit	10 blocks
BuyLowerLimit	Purchasing lower limit	8 blocks
SuggestedPriceRate	Upper limit of a price increment ratio	1%
Lambda_1 (λ_1)	Price sensitivity of the Aggressive bidder agent	-
Lambda_2 (λ_2)	Price sensitivity of the Moderate bidder agent	-
Lambda_3 (λ_3)	Price sensitivity of the Conservative bidder agent	-
FinalRound *	Round with the final decision	-
FinalPrice *	Price with the final decision	-

* Output parameters.

3.2. Model Calibration

The proposed model is calibrated with the result of the IMT auction in 2018 in South Korea. As mentioned in Section 3.1, the auction was devised to sell 28 generic spectrum blocks at 3.5 GHz bandwidth (i.e., 3420–3700 MHz) to three major telecommunication companies. The starting price of the auction was $2348.76 million (i.e., $83.88 million per block). The auction continued until it identified the price where all 28 spectrum blocks were allocated to the three companies. As a result, at the 9th round, companies A, B, and C purchased 10 blocks, 10 blocks, and 8 blocks, respectively. The total contract price was $2651.03 million (see Table 3).

In fact, Company A and Company C paid additional costs for the potential to expand their spectrum blocks in the future by occupying both ends of the IMT spectrum blocks. To calibrate the proposed simulation model, we ignored the bidding price at Stage 2, because the value of the expendability could vary according to the company's strategy. The proposed model was able to complete Stage 1 at the 8th round. Figures 7 and 8 show the trends of bids in terms of the bidding prices and the numbers of spectrum blocks over

multiple iterations. Before the 8th round, all companies tried to maintain their bidding strategies. Because Company C is the Conservative bidder (Type 3) with the minimum competitiveness among the three bidders, it is beneficial to finish the auction when the bidding price is inexpensive. At the 8th round, it tried to decrease its demand from 9 blocks to 8 blocks regarding its maximum capability (see Figure 8). Eventually, the auction was completed when the unit bidding price became $87.29 million per block (see Figure 7).

Table 3. Results of the 3.5 GHz IMT spectrum auction in South Korea in 2018.

Category	Company A	Company B	Company C
Number of spectrum blocks	10	10	8
Bandwidth (GHz)	3.60–3.70	3.50–3.60	3.42–3.50
Bidding price at Stage 1 ($MM)	856.54	856.54	685.23
Bidding price at Stage 2 ($MM)	221.66	-	31.06
Contract price ($MM) *	1078.20	856.54	716.29

* This is the sum of bidding price at Stage 1 and bidding price at Stage 2.

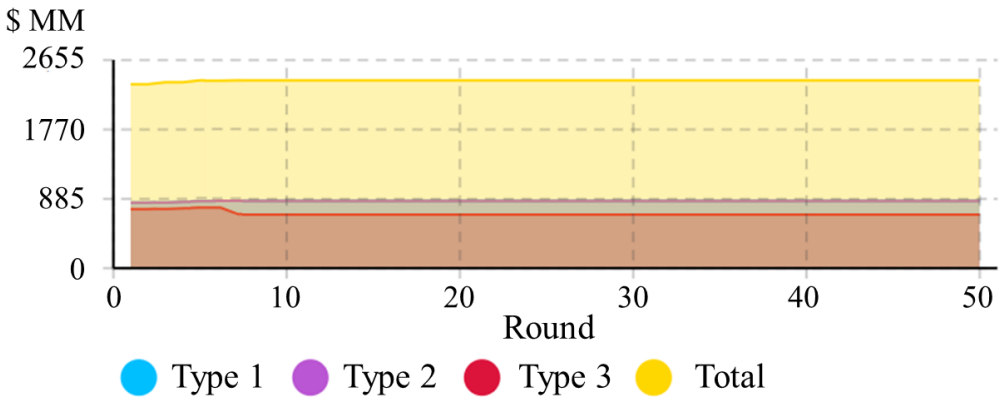


Figure 7. Bidding price over multiple rounds at Stage 1 (purple and blue lines are overlapped).

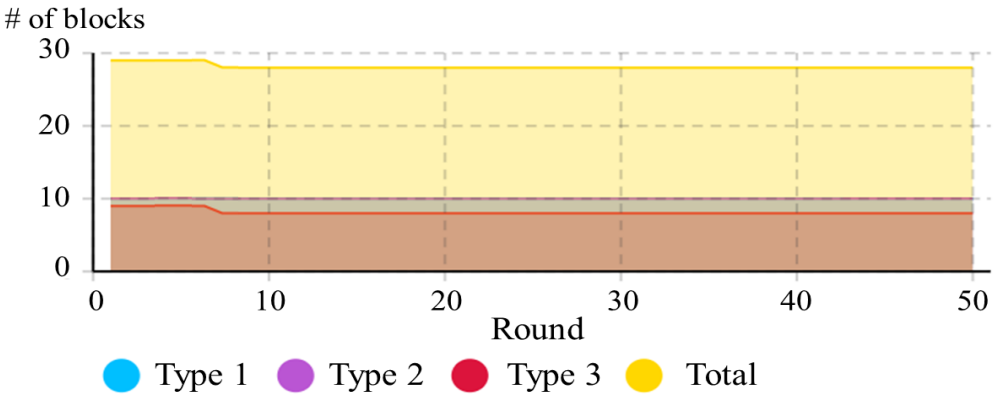


Figure 8. Number of spectrum blocks over multiple rounds at Stage 1 (purple and blue lines are overlapped).

The final bidding prices at Stage 1 for Company A, Company B, and Company C were $872.91, $872.91, and $698.33 million, respectively. R^2 of the simulation was 96.38%. Thus, we believed that the proposed model was successfully calibrated. From the calibration, values of λ_1, λ_2, and λ_3 of 0.001, 0.07, and 0.22, respectively, were achieved. This implies that Company C has the most sensitivity to the bidding price change.

3.3. Case Analysis

In the first case (i.e., low price case), the minimum bidding price was reduced to $1019.20 million (5% of the total annual revenue). Figures 9 and 10 represent the bidding price and the number of spectrum blocks over 50 rounds, respectively. Because of the low initial price, all bidders wanted to buy 10 spectrum blocks, which is the maximum number of spectrum blocks sold to the individual bidder (see Figure 10). This high demand on the spectrum blocks results in continuous increase in the bidding price, and the auction could not be ended. Note that blue, purple, and red lines are overlapped in Figures 9 and 10.

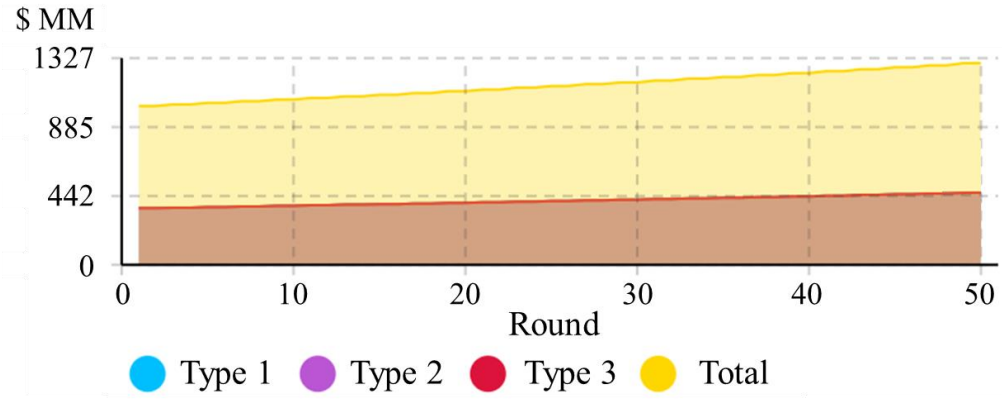


Figure 9. Bidding price over multiple rounds at Stage 1 (low price case).

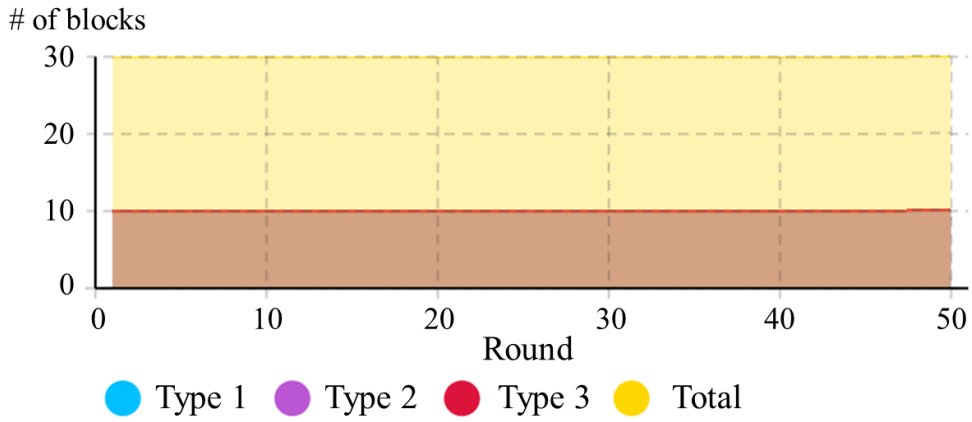


Figure 10. Number of spectrum blocks over multiple rounds at Stage 1 (low price case).

To end the auction, we consider additional demand reduction policy. In this hypothetical policy, each bidder is enabled to reduce its demand during the auction. Figures 11 and 12 show the bidding price and number of spectrum blocks over 50 rounds under the demand reduction policy, respectively. Although most patterns are quite similar to Figures 9 and 10, at the last round, the total demand was for 29 blocks with the total price of $1307.83 million. Interestingly, at the 49th round, Type 3 reduced its demand to 9 blocks with a bidding price of $416.20 million. Regarding Type 3 offering 10 blocks with a bidding price of $457.86 million at the 48th round, its critical bidding price was approximately $460 million. This was 9.34% of the annual revenue of Type 3. This implies that, to be completed within the 50 rounds, the minimum bidding price should be higher that 9.34% of annual revenue of the Conservative bidder (i.e., Type 3). Most blue, purple, and red lines are overlapped in Figures 11 and 12.

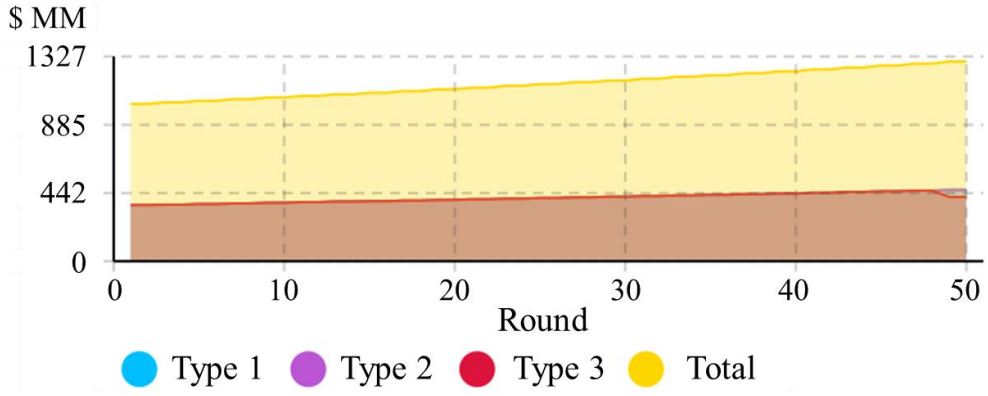


Figure 11. Bidding price over multiple rounds at Stage 1 (low price case with demand reduction policy).

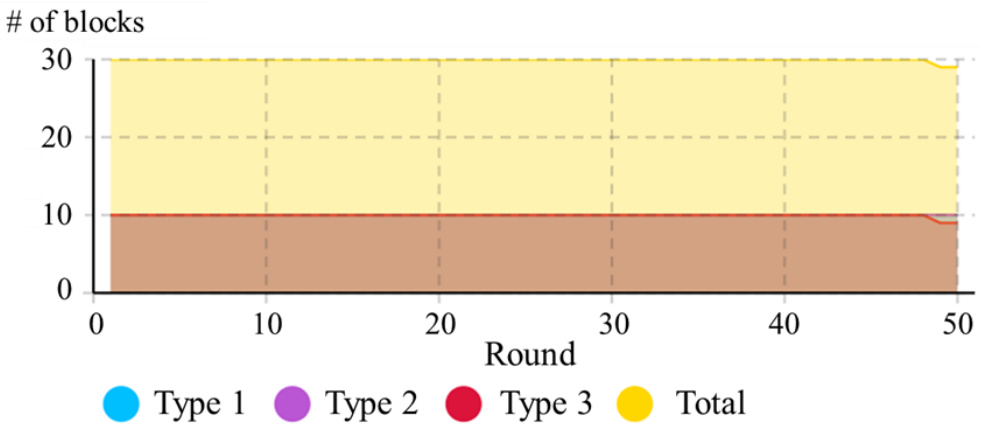


Figure 12. Number of spectrum blocks over multiple rounds at Stage 1 (low price case demand reduction policy).

In the second case (i.e., high price case), the minimum bidding price was increased to \$4076.81 million (20% of the total annual revenue). Figures 13 and 14 reveal the bidding price and number of spectrum blocks over 50 rounds, respectively. Unlike Figures 9 and 10, the Conservative bidder tried to buy the minimum number of spectrum blocks (i.e., 8 blocks) at the beginning of the auction due to its budget shortage (see Figure 13). In the experiment, the total demand was 28 blocks, with the total price of \$4076.81 million at the first round. This implies that, if the initial bidding price (i.e., the minimum bidding price) is too high, the Conservative bidder may not have an opportunity to attend the auction. In fact, this intimidates the fairness of the auction, which was designed to allocate the spectrum blocks without causing adversary impact on the existing mobile telecommunication market [26]. Moreover, if there is no chance for the Conservative bidder, and due to the high minimum bidding price everything is predetermined, there is no reason to have an auction. Note that, in this situation, the allocation results were already finalized at the beginning of the auction. Thus, although the total price of the auction is higher than that of the low price case, it is better to identify an appropriate minimum bidding price that can give fair opportunities to all existing IMT service providers.

To identify the best minimum bidding price at the first round, the optimization model mentioned in Section 2.3.4 was applied. As mentioned in the second case, when the minimum price is too high (i.e., 20% of the total annual revenue), the Conservative bidder cannot have an equal opportunity at the beginning of the auction. To resolve this issue, in this case, we assume that the round with the final decision should be between 6 and

50 rounds (i.e., $\varphi_{min} = 6$ and $\varphi_{max} = 50$ in Equation (13)), and $\tau_{min} =$ \$1019.20 million and $\tau_{max} =$ \$4076.81 million in Equation (12). Figure 15 shows the result of the optimization with a meta-heuristic algorithm in OptQuest® 9.1.2 software.

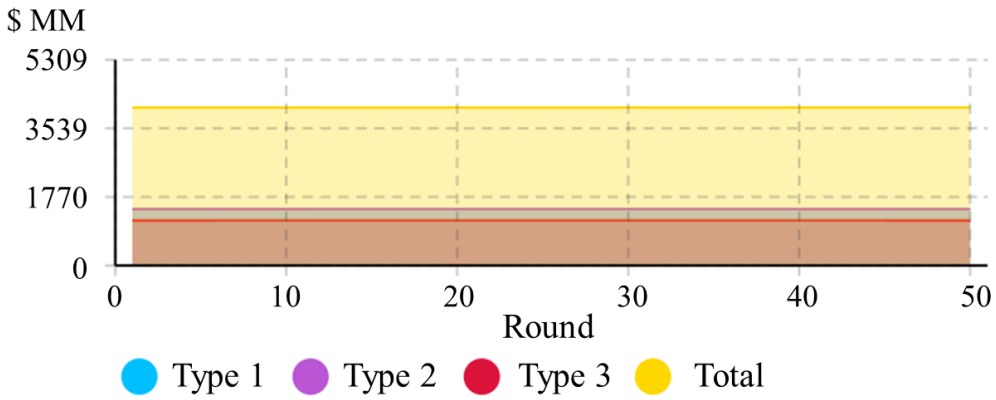


Figure 13. Bidding price over multiple rounds at Stage 1 (high price case).

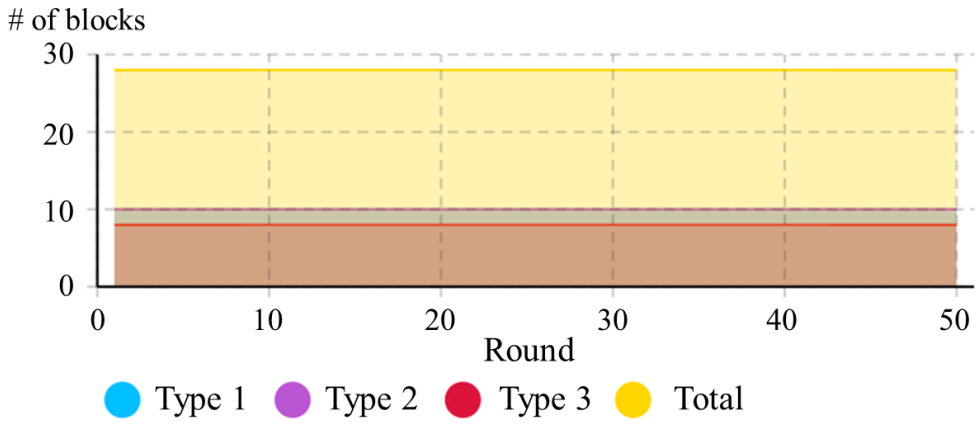


Figure 14. Number of spectrum blocks over multiple rounds at Stage 1 (high price case).

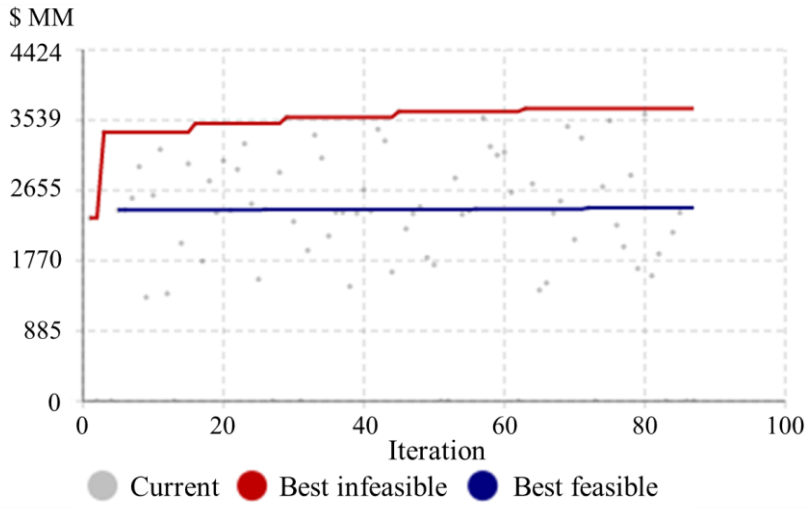


Figure 15. Scenario comparison between the final bidding prices under various minimum bidding prices.

The best minimum bidding price was \$2386.81 million (i.e., \$85.24 million per block). The auction was ended at the 7th round with the price of \$2434.94 million at the first stage.

Note that the minimum bidding price at the IMT spectrum auction in 2018 in South Korea was $2348.76 million (see Section 2.3). The difference between the two values was only 1.62% from $2348.76 million. Regarding the level of significance ($\alpha = 0.05$) associated with statistical estimation from the proposed simulation model and the final contract price of $2651.03 million at the auction, the difference can be negligible. Although there were multiple scenarios with a bidding price higher than $2434.94 million (or $2651.03 million), those solutions were infeasible. In other words, those scenarios cause the issue shown in the second case (i.e., no fair opportunity to the Conservative bidder). In fact, these results explain why the Korea government agency chose $2348.76 as the minimum bidding price. As mentioned earlier, the spectrum auction in South Korea was designed to provide a fair opportunity to all existing IMT companies. This is because the government agency should maintain liberalization of the IMT market (i.e., no sudden change in the market due to the IMT auction designed by government agency). In this sense, the proposed approach can contribute to identifying the best minimum bidding price for healthy and fair competition in the IMT market.

4. Discussion

The proposed approach is devised for the IMT spectrum auction under the CA with an ascending rule, which consists of seven processes including collecting applications, scheduling the auction, conducting the auction, allocating spectrum blocks, payment, cancellation, and documentation. In South Korea, due to the importance of the IMT spectrum management in terms of development in the telecommunication field and its high correlation with the tax-paying budget of the people, the government and related agencies always consider how to design the IMT spectrum auction so that it can provide appropriate benefits to both the participants and the people. This study presents an IMT spectrum auction methodology that utilizes agent-based simulation for the first time. In particular, this study designs three types of auction bidder agents (the Aggressive bidder, the Moderate bidder, and the Conservative bidder) in Section 2.3.1 and the decision-making model of individual agents using the exponential utility theory, as shown in Equation (5). The actual agent demand (see Equation (6)) plays an important role in the auction process, which reflects the main characteristics of the CA determined by the available (or investment) budget, the price sensitivity of each agent, and the suggested price. Figure 4 shows that three types of bidder agents can express the demand for spectrum blocks depending on individual parameters. This shows that modeling or calibration that considers the intention of participants is possible by changing parameters in other IMT auctions. In order to accurately and easily model users' tendencies during the model usage process, a calibration model is presented in Section 2.3.3. It is important to model such diverse decision-making tendencies in auctions, as decision criteria may differ depending on the risk propensity of auction participants [32] and may also change depending on auction policies or participation conditions [33]. In fact, modeling decision-making behavior is a difficult problem, but this study utilizes the exponential utility theory which may simplify a very complex decision-making process relatively through several parameters, as in the model presented in Section 2.3.1. However, the exponential utility theory has been widely used because it is an analytical approach that can accurately analyze given results [34]. In addition, considering that the exponential utility theory has been utilized in modeling studies on existing auction participants [35,36], this study selects the academically proven approach methodology called the exponential utility theory for decision-making behavior modeling.

The performance of the proposed approach is verified through three cases to investigate why the initial bid price setting is important in the spectrum auction and how it

can affect the auction results. First, the proposed calibration model (see Section 2.3.3) accurately calibrates the decision-making model with an R^2 of 96.38%, and simulations for three scenarios are performed; the results are analyzed in Section 3.3. In the low price case (5% of total annual revenue), due to the low initial price, all bidder agents want to purchase 10 spectrum blocks, which is the maximum number of spectrum blocks that can be bid for, and this high demand for spectrum blocks results in the auction not being able to be concluded within the limited number of bidding rounds of 50. This can be judged as an overheated auction that cannot be arbitrated [37], and such failure to bid can lead to a decrease in participants, including the waste of design costs for the auction, as all participants distrust the government-led IMT spectrum auction system [33]. In addition, the subsequent hypothetical analysis (see Figures 11 and 12) also shows that a higher initial price setting is needed to conclude the auction within 50 rounds. In the high price case (20% of total annual revenue), the conservative bidder has difficulty continuing to participate in the auction due to its budget constraint, and this result shows that some participants may be deprived of opportunities if the initial bid price (i.e., minimum bid price) is too high [38]. This is a situation that runs counter to the Korean government's efforts to prevent monopoly markets and promote the coexistence of multiple companies in the telecommunications sector. The experimental result shows that the government and related agencies need to be careful when designing the IMT spectrum auction. As we have discovered through the two previous cases, selecting an appropriate initial bid price is important, and in order to select a fair minimum bid price for all participants, the optimization model based on the simulation-based optimization proposed in Section 2.3.4 has been utilized. As mentioned in Section 2.3, the highest minimum bid price (initial bid price) is \$2386.81 million (i.e., \$85.24 million per block), and the auction ends with a first-round price of \$2434.94 million in the 7th round. This prevents the problem of conservative bidders not having a fair opportunity in the second case and shows that the proposed approach can contribute to identifying the best minimum bid price for sound and fair competition in the IMT market. This shows that the proposed approach can design a fair IMT spectrum auction for all participants in line with the current IMT policy direction of the Korean government.

5. Conclusions

This study has proposed a novel simulation modeling approach for the IMT spectrum auction design under ABS with three telecommunications service provider types (i.e., the Aggressive bidder, the Moderate bidder, and the Conservative bidder). Due to the high-value spectrum rights, it is significant to fairly allocate generic IMT spectrum blocks to existing service providers. To this end, most countries, such as the U.S., Germany, and South Korea, have adopted the IMT spectrum auction as the best way for spectrum block allocation. However, it is challenging to identify the minimum bidding price that can provide fair opportunities to all bidders. If a government agency sets unfair auction rules, it can intimidate liberalization of the IMT market. This should not be happening in countries that are committed to free competitive markets. To overcome the potential problem, the proposed approach has considered the three provider types and their competitiveness in the auction. The exponential utility theory and Vickrey-nearest core pricing theory have been adopted and devised for the realistic decision-making behavior modeling of the agents. The developed ABS was calibrated to the IMT spectrum auction conducted in 2018 in South Korea. Moreover, calibration and optimization models were developed for accurate modeling of the ABS. In particular, the best minimum pricing policy was identified by the meta-heuristic optimization provided by OptQuest®. In the experiments, three cases with different minimum bidding prices (i.e., low price case, high price case,

and the optimal price) were considered and analyzed. As a result, this study found that the minimum bidding price should be designed regarding the budget of the Conservative bidder to provide equal opportunities to all bidders. If the price only tried to maximize the final contract price, there is no reason to have the auction. In this case, only the company with a competitive advantage can buy the IMT spectrum blocks, so that a monopolistic market will appear. The proposed approach will help the government agency prevent this problem in advance.

This study is the first to model the IMT spectrum auction process using agent-based simulation and simulation-based optimization and to suggest the optimal initial bidding price. However, this study has several limitations. First, the case is limited to the IMT spectrum auction in which three Korean companies participated. Although the proposed methodology can model cases with a variety of participants, additional research is needed to determine how appropriately the exponential utility theory and Vickrey-nearest core pricing theory used in the study can model decision-making behavior in the environments of other countries. In addition, the definitions of (1) the Aggressive bidder, (2) the Moderate bidder, and (3) the Conservative bidder need to be changed for each country, and the parameters of the proposed simulation model need to be re-calibrated. Finally, additional data needs to be secured to utilize the proposed methodology. However, since the IMT spectrum auction is not an annual event, but rather a very rare event, such as every 5 or 10 years, it is difficult to collect data for modeling.

For future study, additional behavior data of bidders' decision-making should be collected. The data will help engineers design reliable and fair spectrum auctions involving the minimum bidding price, increment rate, and required number of bidding rounds. In addition, the proposed approach needs to be applied to multiple auction cases in different countries, so that it can be more generalized.

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References

1. Milgrom, P. Putting auction theory to work: The simultaneous ascending auction. *J. Politi. Econ.* **2000**, *108*, 245–272. [CrossRef]
2. Bichler, M.; Goeree, J.K. Frontiers in spectrum auction design. *Int. J. Ind. Organ.* **2017**, *50*, 372–391. [CrossRef]
3. Srinuan, C. The Third Generation (3G) Auction in Asia. *Keio Commun. Rev.* **2011**, *33*, 183–198.
4. Yan, X. 3G licensing in Hong Kong: The debate. *Telecommun. Policy* **2004**, *28*, 213–226. [CrossRef]
5. Jain, R.S. Spectrum auctions in India: Lessons from experience. *Telecommun. Policy* **2001**, *25*, 671–688. [CrossRef]

6. McMillan, J. Why auction the spectrum? *Telecommun. Policy* **1995**, *19*, 191–199. [CrossRef]
7. Chouayakh, A.; Bechler, A.; Amigo, I.; Nuaymi, L.; Maillé, P. PAM: A fair and truthful mechanism for 5G dynamic spectrum allocation. In Proceedings of the 2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Bologna, Italy, 9–12 September 2018.
8. Peha, J.M. Spectrum management policy options. *IEEE Commun. Surv.* **1998**, *1*, 2–8. [CrossRef]
9. Bhattarai, S.; Park, J.M.J.; Gao, B.; Bian, K.; Lehr, W. An overview of dynamic spectrum sharing: Ongoing initiatives, challenges, and a roadmap for future research. *IEEE Trans. Cogn. Commun. Netw.* **2016**, *2*, 110–128. [CrossRef]
10. Bulow, J.; Levin, J.; Milgrom, P. *Winning Play in Spectrum Auctions (No. w14765)*; National Bureau of Economic Research: Cambridge, MA, USA, 2009.
11. Janssen, M.; Kasberger, B. On the clock of the combinatorial clock auction. *Theor. Econ.* **2019**, *14*, 1271–1307. [CrossRef]
12. Islam, S.; Ghosh, S.; Raj, A.; Singh, A.K.; Swain, S.; Bandyopadhyay, A. Efficient Spectrum Allocation: A Simultaneous Multi Round Auction Approach. In Proceedings of the 2024 3rd International Conference for Advancement in Technology (ICONAT), GOA, India, 6–8 September 2024; IEEE: New York City, NY, USA; pp. 1–6.
13. Zeroual, J.; Akian, M.; Bechler, A.; Chardy, M.; Gaubert, S. Optimal Strategy against Straightforward Bidding in Clock Auctions. In Proceedings of the International Conference on Network Games, Artificial Intelligence, Control and Optimization, Lille, France, 8–10 October 2024; Springer Nature: Cham, Switzerland; pp. 83–93.
14. Khadem, M.; Zeinali, F.; Mokari, N.; Saeedi, H. AI-enabled priority and auction-based spectrum management for 6G. In Proceedings of the 2024 IEEE Wireless Communications and Networking Conference (WCNC), Dubai, United Arab Emirates, 21–24 April 2024; IEEE: New York City, NY, USA; pp. 1–6.
15. Kim, S.; Yoon, B. A systematic approach for new service concept generation: Application of agent-based simulation. *Expert Syst. Appl.* **2014**, *41*, 2793–2806. [CrossRef]
16. Kim, Y.; Kim, S.; Kim, S. An integrated agent-based simulation modeling framework for sustainable production of an Agrophotovoltaic system. *J. Clean. Prod.* **2023**, *420*, 138307. [CrossRef]
17. Purbasari, A.; Zulianto, A.; Hidayanto, A.N. Revealed-preference activity rule in combinatorial clock spectrum auction: A review and new research opportunities. In Proceedings of the 2018 IEEE Third International Conference on Informatics and Computing (ICIC), Palembang, Indonesia, 17–18 October 2018.
18. Liu, S.Z.; Hwang, S.H. Survey on co-existence of 5G and satellite earth station in C-band. In Proceedings of the Korean Institute of Communications and Information Sciences (KICS) Conference, Seoul, Republic of Korea, 16 November 2019.
19. Crandall, R.W. New Zealand spectrum policy: A model for the United States? *J. Law Econ.* **1998**, *41*, 821–840. [CrossRef]
20. Basutli, B. Distributed Optimisation Techniques for Wireless Networks. Ph.D. Thesis, Loughborough University, Loughborough, UK, November 2016.
21. Backus, M.; Blake, T.; Masterov, D.V.; Tadelis, S. Is sniping a problem for online auction markets? In Proceedings of the 24th International Conference on World Wide Web, Florence, Italy, 18–22 May 2015.
22. Cramton, P. Spectrum auction design. *Rev. Ind. Organ.* **2013**, *42*, 161–190. [CrossRef]
23. Dimpfl, T.; Reining, A. Price Discovery and Learning during the German 5G Auction. *J. Risk Financ. Manag.* **2021**, *14*, 274. [CrossRef]
24. Bichler, M.; Shabalin, P.; Wolf, J. Do core-selecting combinatorial clock auctions always lead to high efficiency? An experimental analysis of spectrum auction designs. *Exp. Econ.* **2013**, *16*, 511–545. [CrossRef]
25. Munro, D.R.; Rassenti, S.J. Combinatorial clock auctions: Price direction and performance. *Games Econ. Behav.* **2019**, *117*, 195–217. [CrossRef]
26. The Ministry of Science and Information and Communications Technology. Announcement of the IMT Spectrum Auction (No. 2018-235), MIST. Available online: https://eiec.kdi.re.kr/policy/callDownload.do?num=176567&filenum=2 (accessed on 7 January 2025).
27. Ausubel, L.M.; Cramton, P. Auctioning many divisible goods. *J. Eur. Econ. Assoc.* **2004**, *2*, 480–493. [CrossRef]
28. Harsha, P.; Barnhart, C.; Parkes, D.C.; Zhang, H. Strong activity rules for iterative combinatorial auctions. *Comput. Oper. Res.* **2010**, *37*, 1271–1284. [CrossRef]
29. Cramton, P.; Ockenfels, A. The German 4G spectrum auction: Design and behavior. *Econ. J.* **2017**, *127*, 305–324. [CrossRef]
30. Börgers, T.; Dustmann, C. Strange bids: Bidding behaviour in the United Kingdom's third generation spectrum auction. *Econ. J.* **2005**, *115*, 551–578. [CrossRef]
31. Levin, J.; Skrzypacz, A. Properties of the combinatorial clock auction. *Am. Econ. Rev.* **2016**, *106*, 2528–2551. [CrossRef]
32. Vasserman, S.; Watt, M. Risk aversion and auction design: Theoretical and empirical evidence. *Int. J. Ind. Organ.* **2021**, *79*, 102758. [CrossRef]
33. Malisuwan, S. The First Spectrum Auction in Thailand: Lessons Learned and Achievements. *J. Adv. Manag. Sci.* **2017**, *5*, 109–114. [CrossRef]

34. Wood, D.A.; Khosravanian, R. Exponential utility functions aid upstream decision making. *J. Nat. Gas Sci. Eng.* **2015**, *27*, 1482–1494. [CrossRef]
35. Chouayakh, A.; Bechler, A.; Amigo, I.; Nuaymi, L.; Maillé, P. Multi-block ascending auctions for effective 5g licensed shared access. *IEEE Trans. Mob. Comput.* **2021**, *21*, 4051–4063. [CrossRef]
36. Abozariba, R.; Asaduzzaman, M.; Patwary, M.; Naeem, M.K.; Nawaz, S.J.; Sharma, S.K. Secondary spectrum allocation framework via concurrent auctions for 5G and beyond networks. *Wirel. Netw.* **2022**, *28*, 1489–1504. [CrossRef]
37. Gehrig, T. Competing markets. *Eur. Econ. Rev.* **1998**, *42*, 277–310. [CrossRef]
38. Blees, J.; Kemp, R.; Maas, J.; Mosselman, M.; May, Z. *Barriers to Entry*; Zoetermeer, Scientific Analysis of Entrepreneurship and SMEs; The Open University: Milton Keynes, UK, 2003.

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