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Dissertation

Exploring the Limits of Incentive Compatibility and Allocative Efficiency in Complex Economic Environments

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Abstract:
In this dissertation auction formats are developed and discussed that focus on three specific economic environments. Regarding the impossibility results from mechanism design, the main task for the implementation of auction designs is to balance allocative efficiency and incentive compatibility – the main characteristics a mechanism should provide.
Therefore, the dissertation investigates the limits of conceivable relaxations of allocative efficiency and incentive compatibility for complex settings such as double auctions, interdependent-valuation environments and electricity market designs. The overall aim is to carefully weigh up the advantages and disadvantages for either relaxing allocative efficiency or respectively incentive compatibility.

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Markus Reinhardt

Table of contents

Table of abbreviations

■	End of an example or an remark
□	End of a proof
APA	Alternating-Price-Auction
e.g.	for example (abbreviation of Latin “exempli gratia”)
ICDA	Incentive-Compatible-Double-Auction
i. e.	that is (abbreviation of Latin “id est”)
IEMD	Integrated-Electricity-Market-Design
p.	page
pp.	pages
ref.	refer to
VCGm	Vickrey-Clarke-Groves-mechanisms

Preface

The following dissertation was developed at the Chair of Economics and Information Systems of HHL Leipzig Graduate School of Management. First, I appreciate the cooperation with my doctoral supervisor Prof. La Mura. The joined discussions were inspiring and important for the development of my doctoral thesis. Second, I want to thank Prof. Althammer for undertaking the task of the second assessor.

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Markus Reinhardt

1. Introduction

1.1. Applications of auction design

Nowadays, mechanism design and especially auction formats receive increasing scientific and public awareness because of its importance in the organization of many economic and social processes, such as the distribution of energy resources, the allocation of public infrastructure projects, the selling of bandwidth in telecommunications or even the design of voting schemes. This attention arises as mechanism design modifies the perspective on certain problems of economic theory. In fact, the main idea of mechanism design is to propose settings that facilitate the achievement of overall social goals even though rational individuals act according to their own personal interests. Thereby mechanism design follows the concept of competitive situations instead of central regulation to enhance the efficiency of allocation processes. In short, the aim is to find the right synthesis between individual and higher, common benefits. As a consequence, the variable of the concrete economic problem changes from finding optimal strategies for single agents towards the problem of defining an appropriate allocation process that ensures a set of desirable characteristics considering the totality of the participants' desires.

Even though mechanism design is a relatively new research field, first auctions go back to antiquity when auction formats were used in addition to other early trading formats as barter and haggling. It is known that in several ancient cultures of the Western hemisphere, such as those of the Babylonians, Greeks and Romans, auctions were held to trade land, food or slaves or to reallocate the spoils of war between the winning soldiers. Similarly to modern times, auctions were also used to sell valuable objects of household, namely works of art and pieces of furniture. Undoubtedly the most remarkable auction of the antiquity was the sale of the whole Roman Empire by the Praetorian Guard in 193 A.D. after overthrowing the former Emperor Pertinax (ref. Krishna, 2010, p. 2). Didius Julianus offered the highest bid by promising 25,000 sesterces to each of the Praetorian Guard, wherewith he owned the right to become the next Emperor of the Roman Empire.

Nevertheless, auctions in antiquity were used more seldom and relatively sporadic in comparison to other trading formats. After the collapse of the Roman Empire and the involved political realignment of the Western hemisphere, auctions lost economic relevance until the beginning of the modern era. It took until the 17th century for auctions to regain popularity in Europe for the allocation of scarce goods like wine, art and jewelry. Admittedly the most significant upturn of auctions was due to the English and Dutch applications and further developments of auction formats, wherefore the most popular auction designs are named English auction and Dutch auction.

The English auction is the oldest and most common auction format. In the original formulation of the English auction the auctioneer starts the auction with an initial price for the good that is seen as acceptable for many buyers. Afterwards, the auctioneer requests the buyers to overbid the initial price. If one buyer raises the offer, her bid is set the current highest bid and the auctioneer continues the auction by asking for higher bids. This procedure is done until no buyer is willing to offer a higher bid and consequently the auctioneer allocates the good to the buyer with the current highest proposal. Finally, the winning buyer has to pay a trading price that equals her highest bid. As the price is increased monotonically by each step, the English auction is also called open ascending-price auction. Additionally it is presumed that the name “auction”, deviated from the Latin word *augere*, which means *to increase* (ref. Krishna, 2010, p. 2), is due to the ascending-price or English auction.

In contrast to the English auction, the Dutch auction is defined by a decreasing series of trading prices. Starting with an initial price that is seen as too high to be acceptable, the auctioneer lowers the price monotonically by each step of the auction. Finally the good is allocated to the buyer who first signaled to buy the good for the trading price currently proposed by the auctioneer. Due to the fact that the trading price is decreased by each step of the auction, the Dutch auction is also known as open decreasing-price auction.

Nowadays, auctions are widely used in the private sector to trade goods of almost all kinds and their formulations are carefully adapted to the specific economic environments[1]. During the last decade, options to purchase, trade or even to sell goods by an auction rapidly grew. For instance, the opportunities internet-based auction designs offer enable a continuous growth of potential buyers and sellers[2]. Beside the private sector, the public sector is also becoming increasingly aware of the possibilities auctions offer for selling public goods such as spectrum rights, mining rights and infrastructure projects, or even to trade CO_2 abatements. Additionally, governmental institutions facilitate the installation of auctions in private sectors e.g. for the selling of electricity and of natural gas[3].

Considering the multitude of different applications of auctions designs in economic life, the question inevitably arises, which advantages auctions offer in comparison to other market-based concepts like e.g. trade-off, bargaining and fixed-price selling. The main advantage of auctions is its adaptability to the requirements of the economic problem. An auction is defined as a “competition among the buyers according to rules set out by the seller” (ref, Krishna, 2010, p. 61). Obviously, the concrete formulation of the set of allocation rules can vary according to actual conditions of the economic environments and additional goals the auctioneer focuses on.

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[1] The economic environment describes the exogenous parameters, such as individual values, technology and ex-ante resource endowment, which have to be treated as given in allocation problems (ref. Hurwicz, 1972, p.297).

[2] In the last decade e-commerce boomed due to the potentials internet-based auctions offer. The revenue of internet-based auctions such as ebay and Amazon grew by about 500% during the decade (ref. Bailey, 2013).

[3] Following the strategy of the European Comission on renewable energies auction formats are going to get a higher importance for future energy trades in the European Union.

As a consequence, auctions are distinguished, for instance, in the way individual information is collected and for which kind of economic environments they are constructed. First, auction formats differ in the way the individual information is sent to the auctioneer. Consequently, it is distinguished between auctions where agents are asked to send sealed bids, in contrast to those where agents are asked to send open bids to the auctioneer. Furthermore, auction formats differ in the formulation of the pricing rule (e.g. first-price auctions and second-price auctions exist, and the processing, e.g. static auctions or dynamic auctions). Finally, the economic environment has an influence on the formulation of an auction, wherefore auctions are distinguished according to the characteristics of the goods to be traded (e.g. single-unit auctions and multi-unit auctions, and the nature of the values of the agents, e.g. private-value auctions and interdependent-value auctions).

In the following dissertation three concrete economic environments are analyzed and suitable auction formats are presented to adequately distribute scarce goods[4]. The concepts the proposed auctions are based on belong to mechanism design and are briefly introduced in sections 1.2 to 1.4. These sections give only a short introduction into the general concepts of mechanism design and particularly into market-based designs like auctions. For a more detailed discourse about mechanism design refer e.g. to Osborne; Rubinstein, 1994 or Kreps, 1990. For comprehensive information about auction design refer e.g. to Krishna, 2010 or Milgrom, 2004.

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[4] Subsequently, it is formulated which characteristics of an allocation process this paper focus on.

1.2. Optimal use of information in allocation processes

Inseparably compounded with the concepts of mechanism design is the discussion about the correct usage of knowledge in allocation processes. In other fields of economic theory information is treated as completely given to a principal or even to the agents, or at least quantifiable by probability calculations. Assuming that complete information exists and is known to the auctioneer at any time during the allocation process, the problem is well defined and solvable with existing mathematical methods. Difficulties in auction design, for instance, arise as information concerning all relevant facts concerning to the allocation of a certain resource is spread over all market participants (ref. Hayek, 1945, p. 1). Even a central authority, possibly the principal that coordinates the allocation process, does not inevitably have complete information of all relevant aspects concerning the allocation process. Consequently, Hayek notes that the problem of allocating resources cannot be separated from the problem of an effective and efficient usage of the individual information.

Considering the discussion about the correct use of individual knowledge, the main task is to define a market that optimally makes use of the existing information, regardless of whether the information is public or private. As a consequence, the question arises whether the planning process should be centralized by providing the principal with the complete information or if decisions should be made in a decentralized manner (ref. Hayek, 1945, p. 2). Even the concept of collecting knowledge from experts in order to provide the principal with suitable information is limited, as additional individual information exists that can only be used appropriately by working together with each agent. Instead of a centralized planning, perfect competition[5] maintains the efficient usage of knowledge even more. In fact, markets with complete competition are

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[5] Perfect or respectively complete competition is described in Hayek, 1949, p. 95 as a market in which the following conditions concerning the absence of market power, a free market entry and complete information are satisfied:
“1. A homogeneous commodity offered and demanded by a large number of relatively small sellers or buyers, none of whom expects to exercise by his action a perceptible influence on price.
2. Free entry into the market and absence of other restraints on the movement of prices and resources.
3. Complete knowledge of the relevant factors on the part of all participants in the market”.

informationally more efficient than systems based on central planning (ref. Hurwicz, 1960, p. 340), because perfect competition motivates agents to make use of their individual knowledge for bidding. In comparison to regulated markets competitive situations encourage individuals to make use of their personal information in order to increase their outcome.

Assuming that perfect competition is applied to allocate resources, it is inevitable that all participants can expect a non-negative outcome. Otherwise, some of the agents may have an incentive to leave the auction if they anticipate a negative gain from trade. A mechanism in which each agent expects a non-negative outcome is called individual rational. As individual rationality ensures the participation of the agents due to their own rational decisions, it is one of the characteristics a mechanism should satisfy.

Another aspect is that individual revenue and the overall efficiency of a mechanism are conflicting aims. A natural aim of the auctioneer is to allocate the goods to the agents that value it most, irrespective of the economic relevance of reselling[6]. Indeed, the market participants aim to maximize their individual revenue, whereas the auctioneer is interested in maximizing the overall efficiency of the set of trades. As a consequence, the individuals knowing that the auctioneer focuses on the overall gains from trade may adapt their bidding strategy according to the rules of the mechanism in order to get higher revenue from trade. Obviously, bidding honestly must not necessarily be the strategy that maximizes the individual revenue of each agent. Considering the potentially conflicting targets of market participants, governmental institutions and society it is necessary to base the design of efficient mechanisms on a mathematical model to simulate the strategic behavior of rational individuals.

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[6] Following the Coase theorem in markets without transaction costs and with perfect information, inefficiency could be solved by resale after the original trade (ref. Caose, 1960). A recent scientific discourse created several concepts that increase the efficiency of a previous auction by installing a second auction to resell the goods afterwards (ref. Krishna, 2010, pp. 54-60).
Nevertheless, allocative efficiency remains an important property of auctions as transaction cost, time requirements or market entrance barriers cannot be neglected without further consideration.

1.3. Modeling non-cooperative situations

At the same time as Hayek posed his thesis about the correct usage of personal information, von Neumann and Morgenstern founded the fundamentals of the modern-day game theory by publishing their book “Theory of Games and Economic Behavior”. Even if in the 18th and 19h century some isolated game theoretic problems were discussed, it took until the middle of the 20th century to develop a theoretic model to address non-cooperative situations in general. In 1944 von Neumann and Morgenstern introduced the basic principles for the mathematical formulation of economic problems with rational individuals acting according to their personal interests faced with cooperative and competitive economic situations. Beside a general introduction into the modeling and solution concepts of game theory, the authors also provide the answer for finding economic equilibriums[7] in zero-sum games, a class of games in which the earnings equal the losses (ref. von Neumann & Morgenstern, 1953). A few years later Nash extended the existing concepts of game theory to non-cooperative games in general (ref. Nash, 1950)[8]. Therefore, Nash introduced the concept of repeated gaming and showed that there exists at least one equilibrium in mixed strategies for every finite n-person game[9].

The importance of modern game theory is due to the fact that the concepts are applicable to non-cooperative situations in many research fields of economics, physics, biology, social science and computer science. Even if the original scope of application was the modeling of economic behavior, the concepts of game theory were transferred to design competitive situations of any rational individual. Consequently, game theoretical models were used to model problems of population biology, intra-species and extra-species competition and evolutionary

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[7] A set of strategies is called an economic equilibrium if no agent could gain from switching to another strategy while the other agents adhere to their strategies.

[8] In 1994, the Royal Swedish Academy of Science awarded the Nobel Prize in economics to Nash, recognizing the meaning of his paper “Non-cooperative Games” for economic theory.

[9] In contrast to pure strategies where agents repeatedly use the same plan in every game, mixed strategies describes a gaming strategy where agents switch their plan randomly according to an ex-ante defined probability distribution.

theory. An important aspect of game theory is that it provides the term equilibrium as a solution to competitive situations with rational individuals. Thereby game theory also facilitates a different perspective on philosophical problems, such as the social dilemmas of Thomas Hobbes and John Locke.

Beside the development of a wide range of applications for game theory, beginning from the mid 1960th research focused on refining the concept of a Nash equilibrium and developing numerical and analytical methods to solve games. Terms like weak dominance[10], subgame perfection[11] and sequential equilibrium were developed in order to complete the solution concepts of modern game theory. Nowadays, several numerical solution concepts exist that compute at least one equilibrium of a number of non-cooperative games. These are the backward induction for games in extensive form and fictive playing, solving of the corresponding dual problem by linear programming and graphical methods to solve strategic form games. In addition, there exist several specialized solution techniques that take advantage of the specific form of the game.

The scientific discourse about an adequate design of mechanisms for economic and social problems is based on the formalisms game theory provides. Furthermore, it follows that there exists at least one equilibrium for any n-person game, a proposition that is adaptable to auctions. Taking into consideration that there exist plenty of numerical and analytical methods to compute solutions of competitive games, it can be assumed that rational individuals know their optimal response strategy to every possible bidding strategy her opponents use.

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[10] A weakly dominant strategy guarantees the agent an outcome that is at least as high as that of all other possible strategies despite of the other agents’ behavior. In contrast a strictly dominant strategy results in a strictly better outcome for the agent compared the all possible strategies.

[11] If a strategy set that represents a Nash equilibrium in the original game is also a Nash equilibrium of any subgame of the original game, than it is called a subgame perfect equilibrium.

1.4. Motivation for the dissertation

An important question of mechanism design was if it is possible to focuse on the creation of direct-revelation mechanisms, i.e. mechanisms in which the agents directly submit their information to the auctioneer without using an intermediary. The revelation principle developed in several steps by Gibbard, 1973, Green and Laffont, 1977 and Myerson, 1979 indicates that research on incentive compatible mechanisms can be restricted to direct-revelation mechanisms. In fact, for each mechanism that implements a social choice function in dominant strategies there exists an incentive, direct-revelation mechanism that generates the same outcome (ref. Gibbard, 1973, Green & Laffont, 1977 and Myerson, 1979). As a consequence, the scientific research on incentive compatible mechanisms can concentrate on direct mechanisms, as for each mechanism there exists at least one pay-off equivalent direct mechanism.

Considering the basic characteristic a mechanism ha to provide, the requirement of a free market entry, it is important to ensure that the rational individuals join an auction due to their own interest. Consequently, individual rationality is important for the design of a competitive market as an auction design. Another aspect that has to be considered is the fact that knowledge is generally not public. As a consequence, the risk arises that some of the agents try to increase their gains from trade and do not follow the postulated strategies (ref. Samuelson, 1954, p. 389). For mechanisms that are not created appropriately, strategies may exist that allow agents to increase their personal gains from trade by acting dishonestly at the expense of the other participants. Consequently, the aim of achieving an incentive compatible mechanism, i.e. a mechanism that does not offer incentives to signal false values, is regarded as essential to install a fair and transparent allocation process.

Beside incentive compatibility and individual rationality, the concept of fulfilling a certain social choice function is central in mechanism design. The concept is to optimize a social choice function while still ensuring incentive compatibility and individual rationality. An important aspect is that the specific form of the social choice function could be adapted according to the preferences of the mechanism designer[12]. Although other concepts exist, the achievement of allocative efficiency, i.e. the maximization of the total gain from trade, is the most common social choice function. The concept of allocative efficiency follows the idea of allocating scarce goods to the agents that value them most. Obviously, the maximization of the sum of trading benefits is rival to the goal of rational individuals that prioritize maximizing their personal gain from trade.

Inevitably the question arises whether there exist limitations concerning the economic environment or even impossibilities in achieving all the relevant characteristics of mechanism design – incentive compatibility, individual rationality and allocative efficiency – at the same time. It is known that for agents with quasi-linear private utilities the Vickrey-Clarke-Groves-mechanisms[13] are allocative efficient and that bidding truthfully is a dominant strategy (ref. Maskin, 1992, p. 121). Thus, if agents can be assumed to have purely private values, there exists a class of mechanisms that achieve strong characteristics.

Considering the strong characteristics of the Vickrey-Clarke-Groves-mechanisms (VCGm), what kind of problems are left for further studies on auction design? Subsequent, three mechanisms are introduced that focus on specific market-based environments. An accurate study of the assumptions of the proposition concerning the unique properties of the VCGm reveals that they are efficient for economic environments in which buyers have purely private values. Considering

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[12] For instance there exist different concepts for markets that maximize the outcome of sellers or the outcome of buyers or even that of the auctioneer.

[13] The Vickrey-Clarke-Groves-mechanisms describe a class of strategy-proof mechanisms that base on the second-price auction proposed in 1961 by Vickrey (ref. Vickrey, 1961, p. 8). Clarke (ref. Clarke, 1971) and Groves (ref. Groves, 1973) generalized the concept of the second-price auction presented by Vickrey to the multi-unit environment.

two-sided auctions, the VCGm generally fail to balance the sum the buyers spend with the sum the sellers receive, i.e. the VCGm are not budget balanced for double auctions. Furthermore, it is known that efficient and budget balanced allocations are generally not incentive compatible (ref. Myerson & Satterthwaite, 1983). Therefore, the problem of finding mechanisms that balance the conflicting aims of incentive compatibility and allocative efficiency in complex economic environments is central in this thesis. The scientific discourse of the recent years provides several double auctions that are allocative efficient, but only ensure approximate formulations of individual rationality. As a consequence, a double auction for private-valuation environments is introduced that broadens the existing concepts of market design, as it satisfies incentive compatibility, individual rationality, budget balance and asymptotic allocative efficiency also for the complex setting of multi-unit markets with heterogeneous goods. Furthermore, acting honestly is a dominant strategy. The main aspect of the double auction presented in chapter 2 is that individual rationality, budget balance and incentive compatibility are ensured without any assumption concerning the values of the agents or the size of the market. Allocative efficiency can be approximately achieved if the market is sufficiently large and the economic environment provides a homogeneous buyer-seller structure.

Second, in case the values of the agents are affiliated, the classic VCGm fail to achieve ex-post allocative efficiency for markets with more than two agents (ref. Maskin, 1992, pp. 124-125). Consequently, it seems promising to work on avoiding this phenomenon related to the winner's curse[14]. In recent years, several mechanisms – mostly static auctions – were presented that achieve ex-post allocative efficiency. In order to overcome the problem of ex-post inefficiency, existing auctions for interdependent-valuation environments require lots of information from the agents. The core idea of the auction presented in chapter 3 is to limit the amount of information that has to be collected in order to define an ex-

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[14] The winner's curse describes the phenomenon that the winner of a common-value auction may believe to overpay after reconsidering the other agents' bids.

post efficient allocation. Therefore, a dynamic auction is developed that enhances the concept of the Ascending-Bid Auction (ref. Ausubel, 2004) by avoiding the stringent assumptions concerning the buyers bidding strategy. Thereby, the concept of the Alternating-Price Auction proposed in chapter 3 follows the concepts of robust mechanism design (ref. Bergemann & Morris, 2005).

Actually, the study of an adequate dynamic auction for interdependent-valuation environments is limited to one-dimensional values as implementation of efficient allocation processes for multi-dimension values is strongly limited. Considering environments with multi-dimensional, interdependent values an efficient Bayesian implementation is not possible for almost all payoff functions (ref. Jehiel & Moldovanu, 1998, pp. 12-15). Furthermore, for settings with multi-dimensional, interdependent valuation environments it is known that only trivial choice functions are ex-post implementable (ref. Jehiel & Meyer-ter-Vehn & Moldovanu & Zame, 2005, pp. 7-11).

Finally, an electricity market design is presented that combines short and long-term efficiency, which is highly relevant concerning the recent scientific discourse in sustainability and renewable energy. Considering that there is no double auction that fulfills budget balance, individual rationality, incentive compatibility and allocative efficiency, it follows that is complex to follow the conflicting aims of energy-producing companies, investors and operators of network capacities and finally the consumers. In addition, the chronological development has an important influence on the specific auction format as short-term and long-term interests have to be balanced out.

The main task in energy markets is to reconcile the competing interests of the at least four participants, i.e. buyers, sellers, investors and service providers. In contrast to the trade of consumption goods, the trade of electricity, gas or water requires a network to transport the product from seller to buyer[15]. Consequently, it is necessary to pay attention to the interests of investors and operators of the transport network and to balance them with those of the buyers and sellers in order to achieve long-term efficiency. According to recent papers, the main task is to find the right balance between competition and regulation to install an incentive compatible and allocative efficient energy trade. For this reason in chapter 4 an energy allocation process is proposed that uses techniques that are commonly used in optimal flow problems to minimize the transport costs. Due to the inclusion of the network costs into the allocation process, it is possible to construct a mechanism that satisfies short-term and long-term efficiency properties.

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[15] In fact investments in transport capacities are expensive and use large ratio of the gross domestic product (ref. Newbery, 2001, p.27). If these costs shall be refinanced by the trading price per unit it is important to integrate the investments in transport capacities into the allocation process.

2. An Incentive Compatible Double Auction for Multi-Unit Markets with Heterogeneous Goods

Abstract

In the following chapter a double auction for private-valuation environments is presented, which, at the same time, creates an incentive compatible, individually rational and budget balanced allocation, while achieving asymptotic efficiency for large-scale markets with a homogeneous buyer-seller-structure. Thereby, the presented double auction is applicable in single-unit environments, multi-unit environments with homogeneous goods or even in multi-unit environments with heterogeneous goods. In fact, the proposed double auction provides an individually rational and incentive compatible allocation also for multi-unit markets with heterogeneous goods.

In order to achieve incentive compatibility, budget balance and individual rationality, the proposed double auction extracts a subset of agents to calculate a price for each type of good and to define the bundles for the allocation. By excluding the extracted agents from the trade, the main properties incentive compatibility, individual rationality and budget balance can be ensured without additional assumptions concerning the agents' valuation functions.

Furthermore, it is shown that for large-scale markets with a homogeneous buyer-seller-structure the loss of efficiency due to the mechanism becomes negligibly small compared to the overall gains from trade.

2.1. Introduction into double auctions

During the last decade, mechanism design has gained increasing attention within economic theory as the awareness for overall social goals grew. This process is not least due to worldwide financial and economic crises. Especially the rapid expansion of global marketplaces highlights the need for markets that facilitate the creation of individual profits without deferring common interests. Indeed, mechanism design offers settings that encourage people to maximize their personal gains from trade while at the same time acting according to a common social goal. Therefore, especially the theories of mechanism design received increased attention in economic theory[16].

In contrast to the numerous articles that concentrate on the theory of one-sided auctions, the number of papers that focus on double auctions is comparatively small. However, globalized markets and electronic commerce offer varied possibilities for buying and selling goods of almost any type. As a consequence double auctions constructed for large markets are becoming increasingly relevant.

Regarding the existing literature, one of the most important papers concerning double auctions is McAfee's "A Dominant Strategy double auction" (McAfee, 1992). The presented double auction for single-unit environments is individually rational and approximately allocative efficient. In order to generate the trading price and to clear the market, McAfee extracts the least efficient pair of traders. Assuming that the agents' utilities are bounded, the inefficiency is limited and for large markets this loss of efficiency becomes insignificantly small compared to the total gains from trade. Furthermore, acting honestly is a weakly dominant strategy, i.e. bidding according to the individual values is an optimal strategy regardless of other agents' actions.

In fact, the properties a mechanism with two or more agents could simultaneously provide are restricted. Considering the impossibility theorem of Hurwicz, there exists no incentive compatible mechanism that realizes an efficient and individually rational outcome in dominant strategies (ref. Hurwicz, 1972). As a consequence,

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[16] In 2007 the Royal Swedish Academy of Science awarded the Nobel prize in economics to Hurwicz, Maskin and Myerson for their studies on mechanism design and their immense impact in economic theory (ref. The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2007, pp. 1).

the implementation in dominant strategies is often given up in favor of deriving an allocative efficient and individually rational allocation.

Furthermore, Myerson and Satterthwaite demonstrated that efficient and budget balanced allocations are generally not incentive compatible (Myerson and Satterthwaite, 1983). Taking into account that it is impossible to provide a mechanism that guarantees the properties budget balance, incentive compatibility, individual rationality and allocative efficiency at the same time, it is convenient to weaken at least one of these properties in order to enforce the others. In most cases, authors decide to soften the aim of achieving allocative efficiency and budget balance and concentrate on achieving the remaining properties individual rationality and incentive compatibility[17].

If, for instance, one considers the papers of Satterthwaite and Williams (Satterthwaite and Williams, 1989) and (Gresik and Satterthwaite, 1989), the likelihood of gaining from underreporting vanishes at a rate of $o(1/n)$ as the market grows[18]. Satterthwaite and Williams showed that it is getting progressively more complex to find a strategy that creates a higher outcome than that of revealing the truth if the number of agents increases. This property is used for different concepts to limit the incentive incompatibilities of an auction. One extension of McAfee's approach that uses this property was presented in "A Strategy-Proof Multiunit Double Auction Mechanism" (Huang, Scheller-Wolf and Sycara, 2002). This double auction is designed for multi-unit environments with homogeneous goods, and ensures incentive compatibility with respect to the price definition. In addition, this multi-unit double auction is individually rational, weakly budget balanced and approximately allocative efficient. Nevertheless, especially for small markets double auctions such as that from Huang, Scheller-Wolf and Sycara provide incentives for agents to misrepresent their true values in order to be part of the allocation and to increase their gain from trade.

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[17] In contrast to weaker formulations of allocative efficiency or budget balance approximate definitions of individual rationality are more viable. The concept of decreasing incentives to misrepresent the own values if the size of the market grows is studied in Satterthwaite and Williams, 1989.

[18] The integer n defines the number of agents that participate in the auction.

Consequently, an important goal of this paper is to derive a double auction that prevents agents from misrepresenting their true values. Thus, the fact that the scale of future markets is likely to increase offers options to raise the efficiency of the auction while ensuring the other important properties budget balance, individual rationality and incentive compatibility.

Another interesting approach to circumvent the impossibility theorem of Williams and Satterthwaite was developed by Bartal, Gonen and La Mura (ref. Bartal, Gonen & La Mura, 2004). Their idea to facilitate budget balance, individual rationality, incentive compatibility and allocative efficiency for the single-unit market is to compute pairs of agents which are given a price range instead of a definite price for one trade of a single good. As the final definition of the price is subject to negotiations after the auction, the guarantee of efficiency or, respectively, incentive compatibility depends on the concrete form of the negotiation algorithm. Even the enlargement of the price range mechanism to markets with multiple and heterogeneous goods is unanswered.

In conclusion, this paper focuses on developing a double auction that is incentive compatible, budget balanced and individually rational for the complex setting of a multi-unit market with heterogeneous goods. In addition, the mechanism is carefully constructed to limit the loss of efficiency, i.e. to achieve a weaker formulation of allocative efficiency called asymptotical allocative efficiency. The main idea of the double auction is to extract a sample of buyers and sellers in order to use their individual information for the creation of the trading price and the allocation of bundles. Thereby incentive compatibility is ensured due to the structure of the mechanism without further assumptions concerning the valuation function of the agents. For simplicity, the double auction from this chapter is henceforth called Incentive Compatible Double Auction (ICDA).

Following this, the different questions that arise considering the extraction of a group of agents are discussed. How many buyers and sellers should be removed to fix the price? Which are the criteria that define the buyers and sellers that are taken from the original set of agents? Which rule determines the price and how to decide which goods each agent is allowed to trade? All aspects are approached in consideration of the improvement of the properties of the ICDA.

Accordingly, the paper starts in the following section 2.2 with the definition of multi-unit markets with heterogeneous goods and the mathematical definition of the properties budget balance, individual rationality, incentive compatibility and allocative efficiency. Afterwards, in section 2.3, the structure of the ICDA is introduced. In section 2.4 and section 2.5 the different components of the ICDA are derived. Finally, in the last two sections the properties of the ICDA and the characteristics of this approach are discussed in detail.

2.2. Setting of a multi-unit market with heterogeneous goods

Before putting the Incentive Compatible Double Auction (ICDA) into concrete terms, it is necessary to formulate some basic definitions of markets with $r \in \mathbb{N}$ heterogeneous goods. These formulations are needed to discuss the intended properties of the mechanism in detail.

At the beginning, each seller $s_j \in S$ owns $g_k^{(j)} \in \mathbb{R}$ units of good $k = 1, \dots, r$, i.e. her personal portfolio is defined as the set

$$G^{(j)} = \left\{ g_1^{(j)}, \dots, g_r^{(j)} \right\}, j = 1, \dots, n. \tag{2.1}$$

The set of all available goods is defined as

$$G = \left\{ G^{(1)}, \dots, G^{(n)} \right\}. \tag{2.2}$$

As the economic environment of markets with heterogeneous goods allows each seller to sell goods of different types at the same time, it is necessary to consider bundles of goods. Instead of a separate analysis of demand and supply of each good, the valuation has to be carried out by comparing complete packages consisting of goods of different types.

These bundles consist of r quantities – one for each type of good. Consequently, the real-valued vector function

$$v_{s_j}: Q \rightarrow \mathbb{R}_+ , j = 1, \dots , n \tag{2.3}$$

defines the private valuation function of seller $s_j \in S$ that assigns an individual value to each bundle $q \in Q \subset \mathbb{R}_+^r$.[19] The second group of agents that participate in the auction consists of the buyers $b_1, \dots , b_n \in B$ which demand bundles of the r goods from the sellers. Similarly to the formulation from above the private valuation function of buyer $b_i \in B$ is expressed by

$$v_{b_i}: Q \rightarrow \mathbb{R}_+ , i = 1, \dots , m. \tag{2.4}$$ [20]

In addition to the individual valuation function, the agents' utilities of a concrete bundle $q \in Q$ also depend on the market price $p \in \mathbb{R}_+^r$. The k-th component of the price vector $p \in \mathbb{R}_+^r$ corresponds to the price of good $k = 1, \dots , r$. As quasi-linearity is assumed for all agents the utility function of each buyer $b_i \in B$ can be described by

$$u_{b_i}(q, p) = v_{b_i}(q) - q \cdot p , i = 1, \dots , n \tag{2.5}$$

and that of each seller $s_j \in S$ can be defined by

$$u_{s_j}(q, p) = q \cdot p - v_{s_j}(q) \ \ j = 1, \dots , m. \tag{2.6}$$ [21]

Furthermore it is assumed that the participation in the double auction does not create additional effort for the agents.

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[19] The definition of the bundles $q \in Q \subset \mathbb{R}_+^r$ as a real valued vector allows also to trade shares of goods.

[20] In this paper the agents' valuation functions are not restricted to be linear. As a reason the value of a bundle does not have to be equal to the sum of each component's value. This degree of freedom is highly relevant as in real life buyers often look for concrete sets of different goods.
Furthermore, the values depend purely on the agents' own information, i.e. the values are assumed to be private.

[21] A natural assumption for the utility of rational individuals is that effort and earnings of a trade can be separated from each other. Therefore individual utilities are considered to be quasi-linear in this paper.

As a consequence, the utilities of agents who do not trade are assumed to equal zero, i.e.

$$v_b(0) = 0 \quad \forall b \in B$$

and $$v_s(0) = 0 \quad \forall s \in S.$$

To derive the approximate efficiency property of the ICDA in section 2.5 two basic assumptions concerning the utility functions of the agents are needed. First it is convenient to assume that there is at least one specific price vector $\tilde{p} \in \mathbb{R}_+^r$ and respectively one specific bundle $\tilde{q} \in Q$ for every buyer $b \in B$ and every seller $s \in S$ that creates a positive outcome for both. Obviously, this is not a stringent assumption because the agents as rational individuals will only participate in the double auction if they can expect positive revenue.

Analyzing the definition of the agents' valuation functions makes it obvious which conditions are necessary in order to get an individually rational auction. As rational individuals, buyers and sellers will not accept any trade that generates a negative outcome for them. Hence, an agent cannot be forced to trade if she cannot expect to profit. In this case, when no trade is carried out, the agent's utility equals zero.

Considering the utility function of the agents, it is clear that each buyer $b \in B$ will gain from trading a concrete bundle $q \in Q$ as long as $v_b(q) \geq q \cdot p$. Each seller $s \in S$, on the other hand will have a non-negative outcome as long as she sells her bundle $q \in Q$ with a price which is at least as high as her individual valuation, i.e. if $q \cdot p \geq v_s(q)$. Otherwise, the seller will not trade. To ensure the non-negativity of the agents' utilities and thus to ensure the individual rationality of the mechanism, both conditions have to be satisfied for all trades.

Another important property a mechanism should provide is budget balance, i.e. that the mechanism does not earn or lose money. Obviously, this could be achieved if the sum the buyers pay equals the sum the sellers receive for their goods. In order to satisfy this property, the price for each type of good is fixed and the same for all agents. In addition, bilateral trades between one seller and one buyer are used for allocation. The concept of bilateral trades and the fixing of the price guarantees that the ICDA is budget balanced[22].

Finally, the properties incentive compatibility and allocative efficiency, whose achievement is more difficult than that of the other two properties, need to be observed. A mechanism is called incentive compatible if claiming their true types is an optimal strategy for each agent. In other words, it is necessary to ensure that there is no strategy creating a higher outcome than that of acting according to the individual information.

As described above, the social goal this paper focuses on is to achieve allocative efficiency, i.e. to maximize the overall gain from trade[23].

This property can be described as a solution of the following optimization problem

$$\left(\sum_{i=1}^{m} u_{b_i}\left(q_{b_i}, p\right) + \sum_{j=1}^{n} u_{s_j}\left(q_{s_j}, p\right)\right) \to \max_{q_{b_1},\dots,q_{b_m},q_{s_1},\dots,q_{s_n},p} \quad . \tag{2.7}$$

Remembering the discussion from the introduction, it is obviously challenging to get all agents to act truthfully while, on the other hand, maximizing the common gains from trade. The approach of the ICDA to overcome this problem is to concentrate on the achievement of incentive compatibility instead of generating a fully efficient mechanism. Therefore, the structure of the ICDA is carefully constructed to ensure that no agent will have an incentive to misrepresent her true values in order to increase her gain from trade. Although this paper focuses on ensuring incentive compatibility, it is clear that the loss of efficiency needs to be limited. In fact, the loss of efficiency of the mechanism could vanish as the number of agents becomes sufficiently large.

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[22] Subsequent it is presented that the bilateral trades are used to clear the market and to exclude incentive incompatibilities.

[23] The maximization of the overall gain from trade is the most common social choice function in mechanism design. For the sake of simplicity allocative efficiency is often simply called efficiency.

2.3. Concept of the Incentive Compatible Double Auction (ICDA)

Considering the existing concepts for double auctions, incentive incompatibilities arise from the fact that the price definition directly depends on the traders' bids. For instance, the group of k-double auctions (ref. Satterthwaite, 1989) suggests a price that is based on the bids of the least efficient pair of traders. As a consequence, at least one of these agents has an influence on the trading price, i.e. k-double auctions are generally not incentive compatible.

Therefore, the main idea of the ICDA is to extract a subset of agents from the original sets of buyers and sellers. The individual information of the extracted agents is used to calculate the trading price and in addition to generate bundles for the trade. As the information will be used to derive the trading price vector and to define the trading bundles, the selected buyers and sellers have an influence on the allocation process. As a result, the agents may find strategies other than signaling their true values to increase their individual gains from trade. Consequently, the agents that are selected to define the prices must not trade in the ICDA in order to give them no incentive to misrepresent their true values. This is important to ensure that the mechanism is incentive compatible.

Afterwards, the auctioneer allocates the bundles to the remaining agents according to an allocation rule that will be described in section 2.5. This rationing between the agents is necessary to make sure that, on the one hand, the agents are motivated to act honestly and, on the other hand, the overall gain from trade is maximized. Achieving a balance between incentive compatibility and an approximate form of allocative efficiency for the double auction is the main difficulty for the construction of the components price definition rule, bundles creation rule and allocation rule.

Framework of the ICDA

(1) Each agent is asked to send her individual valuation function to the auctioneer.

(2) The auctioneer selects $L = \sqrt{min(m,n)}$ buyers $b_{i_1}, \dots, b_{i_L} \in B$ and L sellers $s_{j_1}, \dots, s_{j_L} \in S$ randomly in order to create the trading prices for each good. The price of good $g = 1, \dots, r$ is computed by using the information of the individual valuations from the selected agents. In addition, the bundles for the auction are computed using the individual information (ref. section 2.5).

As the chosen agents, $b_{i_1}, \dots, b_{i_L} \in B$ and $s_{j_1}, \dots, s_{j_L} \in S$, define the price and the trading bundles, they are removed from the set of the potential traders, i.e.

$$B^- = \bigcup_{l=1}^{L} b_{i_l} \text{ and } S^- = \bigcup_{l=1}^{L} s_{j_l}.$$

Consequently, the set of the remaining buyers is defined as $B^+ = B \backslash B^-$ and that of the remaining sellers as $S^+ = S \backslash S^-$.

(3) Next, the auctioneer allocates the goods according to an allocation rule (ref. section 2.4).

(4) Eventually, the agents $b \in B^+$ and $s \in S^+$ will participate in the auction with a defined trading price of p_g^* per unit for good $g = 1, \dots, r$. The remaining agents $b \in B^-$ and $s \in S^-$ will not trade, hence their utility equals zero.

Remark: In step (2) of the ICDA the trading price vector $p^* = \left(p_g^*\right)_{g=1,\dots,r}$ is computed by using the individual information collected from the selected agents with an arbitrary vector function. The most important fact of the framework of the ICDA is that it creates no incentive for any agent to not act truthfully in order to get a price that may result in a higher individual outcome. This is true as the agents who have an influence on the trading price vector are not allowed to participate in the auction. Furthermore, the concrete formulation of the price function can be used to improve the efficiency property of the mechanism. ■

Before introducing a specific allocation rule, it is convenient to analyze which properties the framework of the ICDA offers independently of the concrete formulation of the allocation rule. First of all, as the principle defines a common trading price p^* and in addition specifies the bundles which are traded, the sellers receive exactly the sum paid by the buyers. As a result, no outside subsidies are needed. Due to the bilateral trades the mechanism is budget balanced.

Besides, the formulation of the ICDA ensures that the agents who trade do not have an influence on the price vector. As a consequence, the agents have no incentive to signal falsely in order to influence the price. But finally, the properties individual rationality and incentive compatibility depend on the chosen allocation rule. The paper focuses on these properties while generating an appropriate allocation rule in section 2.4. As the agents $b \in B^-$ and $s \in S^-$ do not participate in the mechanism, it is obvious that in general the mechanism does not create a completely efficient allocation as the surplus of those agents is lost. Nevertheless, the idea of the ICDA is that the efficiency lost by extracting the sample of agents becomes negligibly small if the market is sufficiently large. Thereby, it is possible to achieve an approximately efficient allocation.

2.4. Definition of the allocation rule

As mentioned in section 2.1, the aim of this paper is to present an auction that achieves budget balance, individual rationality and incentive compatibility at the cost of a less efficient allocation. In the following sections the price definition and the creation of the bundles are derived. Afterwards, the efficiency properties of the ICDA are analyzed in detail. Finally, it is shown that under some assumptions concerning the agents' valuation functions and if the market is large enough the loss of efficiency becomes insignificantly small compared to the total gain from trade, i.e. the ICDA is asymptotically allocative efficient.

A core element of the ICDA is the introduction of an allocation rule to decide how to distribute the trading bundles. Like the price definition in step (2) of the ICDA and the creation of the bundles, which are explained in the following section, the allocation rule plays an important role, as it has to ensure the incentive compatibility and the individual rationality during the distribution process of the bundles. The complexity concerning the allocation rule arises as in addition to the properties incentive compatibility and individual rationality the efficiency of the mechanism has to be observed. Subsequently, a simple allocation rule is presented that ensures incentive compatibility and individual rationality at the costs of a generally low efficiency.

A simple allocation rule (AR1)

a) Before starting the allocation, a random order $b_{i_1}, \dots, b_{i_{m-L}}$ of the buyers from B^+ and a random order $s_{j_1}, \dots, s_{j_{n-L}}$ of the sellers from S^+ are computed.
The price vector $\tilde{p} \in \mathbb{R}_+^r$ is computed using an arbitrary function.

b) Afterwards $z = min(m - L, n - L)$ different bundles $q_1, \dots, q_z$ of the heterogeneous goods are built by using the information of the extracted agents from $B^-$and S^-. [24]

c)
```
For $k = 1$ to $z$

    If $u_{b_{i_k}}(q_k, \tilde{p}) \geq 0$ and $u_{s_{j_k}}(q_k, \tilde{p}) \geq 0$ then

        $b_{i_k}$ buys the bundle $q_k$ from $s_{j_k}$

    Else

        $b_{i_k}$ and $s_{j_k}$ will not trade

    End

Next

All agents with an index that exceeds $z$ will not trade.
```

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[24] The concrete formulation of the bundle creation rule of the ICDA is presented in section 2.6. Certainly the allocation rule (AR1) could be used with any bundle creation rule.

Proposition 2.1: Regarding an arbitrary trading price vector $\tilde{p} \in \mathbb{R}_{+}^{r}$ and an arbitrary bundle creation rule, the simple allocation rule (AR1) is individually rational and incentive compatible without further assumptions.

Proof: Each agent is asked once if the proposed bundle is deemed acceptable. Therefore no agent is forced to trade if the bundle is not worth enough. Consequently, the allocation rule is individually rational as no agent is forced to trade if the expected gain from trade is negative.

As there is exactly one offer by the auctioneer and the order of the agents is created randomly, the buyers and sellers have no incentive to signal falsely in order to get another bundle. Obviously, the optimal strategy for each agent is to accept the bundle offered if and only if the individual utility is non-negative. As a result, the allocation rule is individually rational and incentive compatible at the same time. □

When analyzing the simple allocation rule (AR1), some properties can be found quite easily. It is advantageous that it is not necessary to introduce supplementary assumptions concerning the agents' valuation functions to ensure individual rationality and incentive compatibility. Additionally, the structure of the allocation rule itself is straightforward, comprehensible for the agents and easy to implement.

On the other hand, the disadvantages of the simple allocation rule are quite obvious. A trade between one buyer and one seller is executed if and only if the bundle is constructed in a way that the utilities of both agents are non-negative. Furthermore, the individual preferences of the agents are not used to increase their gain from trade. The efficiency of the simple allocation rule directly depends on the homogeneity of the agents' preferences and in addition on the precision with which the bundles are constructed. In general the simple allocation rule creates a quite inefficient allocation.

In order to improve the efficiency of the allocation rule, it is essential to install a mechanism that allows the agents to choose between different bundles. As the following allocation rule pays more attention to the agents' preferences, it creates a higher total surplus from trade.

An approximately efficient allocation rule (AR2)

a) Before starting the allocation, a random order $b_{i_1}, \dots, b_{i_{m-L}}$ of the buyers from B^+ and a random order $s_{j_1}, \dots, s_{j_{n-L}}$ of the sellers from S^+ are computed. The price vector $\tilde{p} \in \mathbb{R}_+^r$ is computed using an arbitrary function.

b) Next, $z = min(m - L, n - L)$ different bundles $q_1, \dots, q_z$ of the r different goods are built by using the information of the extracted agents from B^- and S^-. [25]

c) Each bundle $q_1, \dots, q_z$ that creates a net surplus (considering the trading price vector $\tilde{p}$) is put on the agent's individual preference list. These preference lists are sorted in an ascending order according to the bundles' individual value.

d) Afterwards, the following conditions have to be satisfied:

   d1) All bundles that are in the first position of the preference list of any buyer b_{i_k} are removed from the preference list of buyer b_{i_l} with $l = k + 1, \dots, m - L$. This is done for all buyers b_{i_k} with $k = 1, \dots, m - L - 1$ and in the equivalent way for all sellers s_{j_k} with $k = 1, \dots, n - L - 1$.

   d2) If the number of available bundles exceeds the number of buyers or the number of sellers, then the according number of bundles, beginning with the highest index, are removed[26].

e) Finally, the remaining agents are allowed to trade the bundle that is in the first position of their latest preference list.

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[25] The concrete formulation of the bundle creation rule of the ICDA is presented in section 2.6. Certainly the allocation rule (AR2) could be used with any bundle creation rule.

[26] In order to ensure that d1) and d2) are satisfied, both steps may have to be repeated iteratively.

Proposition 2.2: The conditions d1) and d2) of allocation rule (AR2) do not create incentives to signal false preferences to the auctioneer.

Proof: First of all, as the auctioneer allocates a bundle to the buyer with the smallest index and respectively to the seller with the smallest index, according to the randomized orders from step a), the agents are indifferent to removing bundles from their preference list when they are preferred by a predecessor. This is true, because if this bundle is traded and there are multiple solutions for the allocation, the buyer or seller with the smallest index will get this bundle. Therefore, condition d1) does not create incentives to misrepresent the true values.

Second, it is obvious that a single agent has only little influence on the number of agents involved in the mechanism. It is clear that an agent cannot gain from pretending to have an empty preference list and leaving the auction. On the other hand, it is not possible for an agent to force other agents to stay in the mechanism if they cannot find bundles with an expected surplus or to leave the auction if it is beneficial for them to trade. As a result, no agent has an influence on reducing or increasing the number of agents.

Hence, condition d2) is incentive compatible, too. □

Proposition 2.3: Conditions d1) and d2) of allocation rule (AR2) guarantee that the allocation found in step e) of (AR2) is unique.

Proof: Considering condition d2) it is guaranteed that the number of buyers and respectively the number of sellers is at least as high as the number of goods that are still available. If this is combined with condition d1), it is clear that all buyers have different bundles in the first position of their final preference lists.

Therefore, all remaining bundles relate to exactly one first position of one buyer's and respectively one seller's preference list. Consequently, there exists only one unique solution of (AR2). □

Proposition 2.4: The allocation rule (AR2) is individually rational and incentive compatible. Furthermore, (AR2) is strategy proof. [27]

Proof: First, the individual rationality of (AR2) is ensured because only preferences are considered for which the individual utility is positive. As a result, each buyer and each seller either gets a bundle that surely creates a positive outcome or they will not trade. Consequently the agents' gains from trade of (AR2) are non-negative.

Second, the incentive compatibility is guaranteed as conditions d1) and d2) are incentive compatible. Due to the rule that only the first choice is allocated to each agent, it is clear that signaling the true values to the auctioneer is an optimal strategy independently of other agents' strategies. As a consequence, (AR2) is strategy proof. □

Considering the findings of the previous sections, the ICDA framework in combination with (AR2) forms a budget balanced, incentive compatible and individually rational multi-unit double auction. These properties are guaranteed without any assumptions concerning the utility functions of the agents. Finally, the investigation of the efficiency of the ICDA including the allocation rule (AR2), depends on the price definition.

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[27] A mechanism is called strategy proof, if revealing the true type is a dominant strategy for all agents.

Therefore, in section 2.5 the price definition rule and the construction of the bundles are developed. Afterwards, in section 2.6 the properties – including also a proposition about the efficiency rate – of the ICDA are discussed.

2.5. Creation of the price vector and the trading bundles

In the previous sections the basic framework of the ICDA and concrete allocation rules were presented. The main focus for these components of the ICDA is to ensure the properties incentive compatibility, individual rationality and budget balance independently of the structure of the valuation functions of buyers or sellers. In addition, the allocation rule (AR2) is designed to limit the loss of efficiency. Finally, the questions of how to define the bundles that could be traded and how to create an appropriate price for each good are still unanswered.

Both the definition of the price vector and the definition of the set of the trading bundles have direct influence on the efficiency of the ICDA. As the other intended properties incentive compatibility, individual rationality and budget balance are already ensured, it is possible to design the price vector and the set of trading bundles in a way that maximizes the allocative efficiency.

An allocative efficient mechanism is defined as a mechanism that maximizes the overall gains from trade, i.e. which maximizes the sum of the agents' net surpluses. If it is assumed that the auctioneer has complete information about the valuation functions of the buyers and the sellers, allocative efficiency can be achieved by solving the maximization problem

$$\left(\sum_{i=1}^{m} u_{b_i}(q_{b_i}, p) + \sum_{j=1}^{n} u_{s_j}\left(q_{s_j}, p\right)\right) \rightarrow \underset{q_{b_1},\dots,q_{b_m},q_{s_1},\dots,q_{s_n},p}{max} \quad . \tag{2.8}$$

Considering the statements about budget balance and individual rationality, it is obvious that the unrestricted formulation of the optimization problem may prevent the auction to be budget balanced and individually rational. Clearly, the unrestricted formulation of the optimization problem has to be modified in order to also facilitate budget balance and individual rationality.

As a consequence, the following conditions

$$u_{b_i}(q_{b_i}, p) \geq 0, \qquad i = 1, \ldots, m \tag{2.9}$$

$$u_{s_j}\left(q_{s_j}, p\right) \geq 0, \qquad j = 1, \ldots, n$$

and

$$\sum_{i=1}^{m} q_{b_i} = \sum_{j=1}^{n} q_{s_j} \tag{2.10}$$

are added to the unrestricted optimization problem (2.8)[28]. The result of the optimization problem provides the price vector and the trading bundles for a double auction with heterogeneous goods.

Considering the remarks about incentive compatibility above, it is quite obvious that it is not possible to use the information of all agents' preferences because this would create incentives to increase one's personal outcome by misrepresenting one's true values. Therefore only the valuation functions of the agents that are taken out of the original sets and will not trade can be used for computing the optimal price vector and the trading bundles.

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[28] These constraints are necessary to ensure that the outcome for each agent is non-negative and that the payments equal the earnings. As the ICDA uses bilateral trades it is enough to assume that the number of sold goods equals the number of bought goods. Thus the solution of the optimization problem also pays attention to the properties budget balance and individual rationality.

Consequently, the price vector and the bundles of the ICDA are computed by solving the optimization problem

$$\left[\sum_{l=1}^{L} u_{b_{i_l}}\left(q_{b_{i_l}}, p\right) + \sum_{l=1}^{L} u_{s_{j_l}}\left(q_{s_{j_l}}, p\right)\right] \rightarrow \max_{q_{b_{i_1}},\dots,q_{b_{i_L}},q_{s_{j_1}},\dots,q_{s_{j_L}},p} \tag{2.11}$$

with the constraints

$$u_{b_{i_l}}\left(q_{b_{i_l}}, p\right) \geq 0, \qquad l = 1, \dots, L \tag{2.12}$$

$$u_{s_{j_l}}\left(q_{j_l}, p\right) \geq 0, \qquad l = 1, \dots, L$$

and

$$\forall b_{i_l} \in B^- \ \exists s_{j_k} \in S^- \ : q_{b_{i_l}} = q_{s_{j_k}}. \tag{2.13}$$

Taking into account that bilateral trades are used in the ICDA for the exchange of goods, the third restriction of the optimization problem has to be modified. Instead of the overall sum of traded goods the number of traded goods for each deal has to be equal[29].

Eventually, the price definition of the ICDA depends on the solution of the nonlinear optimization problem (2.11), for which reason the theory about solving (2.11) is important for the numerical implementation of the ICDA. Considering, for instance, the third constraint, it is clear that in general the optimization problem (2.11) has more than one solution. There exist several numerical methods such as penalty algorithms, evolutionary algorithms or algorithms based on the steepest descent that provide adequate approaches for an effective and efficient solution of (2.11).

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[29] Obviously the modification of the third constraint generally leads to a lower efficiency. In the following chapter it is shown under which assumptions asymptotical allocative efficiency can still be achieved.

2.6. Characteristics of the Incentive Compatible Double Auction (ICDA)

In the previous sections the structure of the ICDA and the formulation of the different components of the ICDA were developed. The focus of these sections was to install a double auction that ensures the properties budget balance, incentive compatibility and individual rationality without further assumptions. As a summary, the ICDA is budget balanced, individually rational and incentive compatible without any assumptions concerning the agents' valuation functions.

Finally, the proof of the efficiency property of the presented double auction is addressed in this section. Therefore, the assumptions, ensuring that the allocation computed by the ICDA is approximately allocative efficient, are discussed.

Definition: A mechanism is called asymptotically allocative efficient if the loss of efficiency becomes negligibly small compared to the overall gain from trade when the number of agents is sufficiently large.

Proposition 2.5: Considering multi-unit auctions, the ICDA is asymptotically allocative efficient, if the conditions

(2.14) the valuation functions of the buyers are limited by an upper bound

$\max_{b \in B, q \in Q} v_b(q) \leq \overline{v}$ for a $\overline{v} \in \mathbb{R}_+$

(2.15) there exist a lower bound $\underline{v} \epsilon \mathbb{R}_+$ with:
for each buyer $b_i \in B$ there is a subset $\bar{Q}_{b_i} \subset Q$ for which at least one $\bar{q} \in \bar{Q}_{b_i}$ exists that $v_{b_i}(\bar{q}) > v_{b_k}(\bar{q}) \quad \forall \quad k = 1, \dots, n; k \neq i$
and additionally $v_{b_i}(\bar{q}) - \min_{k=1,..,m} v_{s_k}(\bar{q}) \geq \underline{v}$ holds,
for each seller $s_j \in S$ there is a subset $\bar{Q}_{s_j} \subset Q$ for which at least one $\bar{q} \in \bar{Q}_{s_j}$ exists that $v_{s_j}(\bar{q}) < v_{s_k}(\bar{q}) \quad \forall \quad k = 1, \dots, m; k \neq j$ holds
and additionally $\max_{k=1,\dots,n} v_{b_k}(\bar{q}) - v_{s_j}(\bar{q}) \geq \underline{v}$ holds,

(2.16) all buyers' valuation functions are taken from the same distribution and all sellers' valuation functions are taken from the same distribution, i.e. $\forall b \in B: v_b \sim V_b$ and $\forall s \in S: v_s \sim V_s$

(2.17) the agents' valuation functions are independent

are satisfied.

Proof: First, it is important to show that for $m, n \rightarrow$ the possibility that each agent could trade an acceptable bundle converges to 1, if condition (2.15) is fulfilled. Within the price definition from the ICDA, the information from the sample of agents extracted in step (1) is used to approximate the valuation distributions of buyers and sellers. According to mathematical statistics, an empirical distribution function converges almost surely to the true distribution function if condition (2.16) and (2.17) hold and the size of the sample converges to infinity. Consequently, the information of the sample is a good approximation for the exact distribution function of the agents' valuations if L is sufficiently large. This is true because the assumption $L = \sqrt{min(m, n)} \rightarrow$ holds.

Finally, it is necessary to show that the loss of efficiency due to the extraction of a subset of agents converges to zero if the market is sufficiently large.

Regarding assumption (2.14), the loss of efficiency from the extraction of the sample is limited by

$$L \cdot \left(\max_{b \in B, q \in Q} u_b(q, p^*) + \max_{s \in S, q \in Q} u_s(q, p^*) \right) \leq L \cdot \bar{v}.$$

As long as the net surplus of the trades grows faster than $L \cdot \bar{v}$, the loss of efficiency caused by the extraction of the agents in step (1) of the ICDA becomes negligibly small. This is true because according to assumption (2.15) there exists a solution to the optimization problem (2.11) in which each agent gets the chance to trade an acceptable bundle. In fact, for each $p \in \mathbb{R}^r_+$ and each $b \in B$ with $\overline{q} \in Q$ exists for which $v_{b_i}(\bar{q}) - \min_{k=1,..,m} v_{s_k}(\bar{q}) \geq \underline{v}$.

Consequently, the loss of efficiency due to the extraction of the sample becomes negligibly small compared to the total surplus of the allocation, i.e.

$$\frac{\sum_{b_i \in B^-} u_{b_i}\left(q_{b_i}, p^*\right) + \sum_{s_j \in S^-} u_{s_j}\left(q_{s_j}, p^*\right)}{\sum_{b_i \in B^+} u_{b_i}\left(q_{b_i}, p^*\right) + \sum_{s_j \in S^+} u_{s_j}\left(q_{s_j}, p^*\right)} \leq \frac{L \cdot \left(\underset{b \in B, q \in Q}{max} v_b(q) - \underset{s \in S, q \in Q}{min} v_s\,(q)\right)}{z \cdot \underline{v}}$$

$$\leq \frac{L \cdot \overline{v}}{z \cdot \underline{v}} = \frac{\overline{v}}{\underline{v}} \cdot \frac{L}{min(m,n) - L} = \frac{\overline{v}}{\underline{v}} \cdot \frac{L}{L^2 - L}$$

$$= \frac{\overline{v}}{\underline{v}} \cdot \frac{1}{L - 1} \xrightarrow[m,n \to]{} 0$$

As a consequence, the ICDA is asymptotically allocative efficient if conditions (2.14) to (2.17) of the proposition above are satisfied. □

Remark: Regarding the conditions from above, (2.17) is needed to ensure homogeneity of the buyer-seller structure if multiple goods have to be allocated. Therefore, it follows that if the ICDA is applied for single-unit auctions it is asymptotically allocative efficient even without (2.15). In worst case, if there is no similarity between the buyers' acceptable bundles and the sellers' acceptable bundles the ICDA will not compute an adequate allocation. ■

To complete the review of the efficiency of the ICDA, it is necessary to analyze the ICDA if conditions (2.14) or (2.15) are not satisfied. First, condition (2.14) is needed to limit the loss of efficiency that occurs from the extraction of agents from the original set of traders. Obviously, the maximum valuation of each agent for one bundle has to be bounded by a $\bar{v} \in \mathbb{R}^+$. Otherwise, if an agent's valuation for a single bundle cannot be limited, i.e. becomes infinitely large, the loss of efficiency cannot be balanced in case this agent is extracted. Analogously, it is necessary to ensure that the utility of a trade has a lower bound. Both assumptions are close to real life and no strong limitations.

The similarity condition (2.15) ensures that every buyer could find a seller with the bundle that is acceptable for both of them. If condition (2.15) is not satisfied, then the ICDA will not converge to asymptotic efficiency even if condition (2.14) is true. That characteristic is due to the definition of the ICDA that allows only bilateral trades in order to ensure incentive compatibility. In the worst case, if there is no overlap between the distributions of the buyers' and sellers' valuation functions, no trade will be carried out and consequently the efficiency equals zero.

2.7. Discussion of the properties of the Incentive Compatible Double Auction (ICDA)

In the previous sections a double auction is presented that focuses on achieving a budget balanced, individually rational and incentive compatible allocation in single-unit as well as in multi-unit markets with heterogeneous goods. Due to this concentration on achieving incentive compatibility without any assumption concerning the agents' values or bidding behavior, the resulting efficiency of the ICDA directly depends on the homogeneity of the buyer-seller-structure. The minimum requirement of the ICDA is that each buyer could find at least one bundle acceptable to trade it with a seller and vice versa.

One element of the ICDA to ensure incentive compatibility is the bilateral trade that is used during the allocation phase of the double auction. A conceivable relaxation would be to replace the one-on-one trade of (AR2) in step (3) of the proposed double auction by a continuing trade rule. For this, the order of the buyers and sellers computed at the beginning of (AR2) is also used to allocate the goods. Starting with the lowest index $l, h = 1$ each buyer $b_{i_l}, l = 1, \dots, m - L$ and each seller $s_{j_h}, h = 1, \dots, m - L$ trades her preferred bundle as long as the remaining demand or respectively the remaining offer is sufficient. It is obvious that in the worst case the allocation would conclude with $2 \cdot r$ agents not having been able to trade their complete bundle. As a consequence, these $2 \cdot r$ agents may have an incentive to signal false values during the allocation phase in order to increase their individual gain from trade. The incentive to act dishonestly could be reduced by the auctioneer with a compensation for the open trades at the cost of the budget balance of the double auction. Certainly, even with such a compensation by the auctioneer an incentive for the up to $2 \cdot r$ agents remains to increase their gains from trade by acting dishonestly. Therefore, the ICDA was developed to consequently exclude incentives to misrepresent the true values.

In summary, the Incentive Compatible Double Auction (ICDA) provides the important properties budget balance, individual rationality, incentive compatibility and strategy proofness without any assumptions concerning the agents' individual valuation functions, even for the complex economic environment of a multi-unit market with heterogeneous goods. Thereby the ICDA enlarges the existing approaches of double auctions, which predominantly concentrate on the efficiency of the mechanism and as a result only achieve approximate formulations of incentive compatibility or budget balance. Especially for the complex economic environments of markets with several heterogeneous goods, the ICDA strikes a new path.

Due to the structure of the mechanism, the achievement of approximate allocative efficiency for multi-unit markets depends on the homogeneity of the agents' valuation functions. In order to achieve efficiency, a kind of symmetry between the distribution of the valuation functions of buyers and sellers is needed. Ensuring the approximate formulation of allocative efficiency requires that each buyer could find a seller for a one-on-one trade. Otherwise, it is not guaranteed that the ICDA will achieve approximate allocative efficiency even if the number of agents increases. By contrast, for the less complex single-unit market the approximate efficiency is also ensured without assumption (2.15) concerning the agents' valuations. As a consequence, the field of application in multi-unit markets is close to economic environments that provide the required symmetry between buyers and seller. Markets of goods that are naturally summed up in sets, such as markets for the sale of stamps or coins, ensure the buyer-seller symmetry needed.

Actually, the dependence of the efficiency property on the similarity of the buyers' and the sellers' preferences is due to the bilateral trades used for the allocation. Certainly, bilateral trades are needed in the ICDA to clear the market, preventing incentive incompatibilities. A modified double auction that also allows trades between groups of buyers and sellers instead of using only bilateral trades is conceivable. However, the use of an allocation rule that is based on multilateral trades would increase the efficiency properties of the ICDA at the expense of incentive compatibility.

3. An Alternating-Price Auction for Interdependent-Valuation Environments

Abstract

In the following chapter a dynamic auction is presented that computes an incentive compatible and ex-post efficient allocation for multi-unit environments with bidders having interdependent values. The concept of the dynamic auction is to implement several rounds of biddings to enclose an ex-post efficient allocation.

To achieve this, the auctioneer announces varying trading prices each round and afterwards reveals the corresponding biddings of all agents. Additionally, the proposed double auction requests less individual information from the buyers as known static auctions.

Due to the concept of announcing prices and revealing the bids, the dynamic auction constructs an allocation that is incentive compatible, individually rational and ex-post efficient at the same time. Therewith, the Alternating Price Auction enhances the existing concepts of simultaneous ascending-bid auctions that make explicit assumptions concerning the bidding behavior.

3.1. Introduction into ex-post efficient auction design

Even 60 years after its publication, Vickrey's article “Counterspeculation, Auctions and Competitive Sealed Tenders” is still one of the most important papers of mechanism design, providing the fundamentals for implementing an incentive compatible and efficient auction. The main aspect of Vickrey's analysis is that first-price auctions assist rational individuals to misrepresent their true values (ref. Vickrey, 1961, pp. 20-22). Indeed, agents may find strategies other than bidding truthfully to increase their individual gain from trade. Consequently, bidding truthfully is not a dominant strategy if the price is set according to the first price rule.

Moreover, Vickrey's solution to overcome the direct dependence between trading price and winner's bid is to install auctions in which the winner has to pay a price equal to the second highest bid. The implementation of the second-price rule effects that truth-telling becomes a weakly dominant strategy in private-valuation environments.

Unfortunately, the VCGm fail to achieve ex-post efficient allocations if the buyers' values are affiliated[30]. In short, difficulties arise when the agents reconsider their bids after getting information about the opponents' bids. This observation of the opponents' bids could happen during the auction or even after it, when the goods have already been allocated. Due to the unique properties of the VCGm[31] there are several papers that attempt to extend their principles to interdependent-valuation environments. Among others, Milgrom and Weber developed a mechanism based on the concept first proposed by Vickrey, which offers better properties for interdependent-valuation environments (Milgrom and Weber, 1982). They presented a second-price auction which is efficient for symmetric bidders whose values satisfy a single-crossing property.

Another interesting approach among the group of static auctions for interdependent-valuation environments was published in Dasgupta's and Maskin's paper "Efficient Auctions". The proposed auction is based on giving the auctioneer more information about the buyers' valuation functions. Therefore, each agent is asked to send her bidding strategy regarding all possible offers by other agents to the auctioneer who afterwards computes an allocation by using this information. Obviously this auction forces the agents to reveal their personal information, for which reason it is not detail-free[32]. However Dasgupta's and Maskin's

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[30] In 1992 Maskin showed that for a single-unit-market with two buyers whose valuations are interdependent the VCGm are ex-post efficient while for environments with more than two buyers standard simultaneous mechanisms fail to achieve ex-post efficiency in interdependent valuation environments.

[31] The generalized VCGm maximize the outcome among all efficient auctions for multiple goods (ref. Krishna, Perry, 1997, p. 4).

[32] In 1985 Wilson analyzed the existing approaches of auction design whereat he created the request that auctions have to be less dependent of the bidders' valuation function and the joint distribution of the private information. Auctions that do not directly depend on the agents' values are called detail-free.

generalization of the VCGm generates an ex-post efficient outcome for agents having interdependent, one-dimensional values (ref. Dasgupta, Maskin, 2000, p. 361).

A different concept to achieve ex-post efficiency for interdependent-valuation environments is to give the buyers the chance to reconsider their biddings by revealing the offers of all agents. One of these mechanisms was proposed by Perry and Reny in 2002. The authors suggest an auction in which each agent is given the chance to reconsider her initial bid by gathering information about the bids of her opponents (ref. Perry & Reny, 2002). Perry and Reny manage this by revealing the first-round bids of all agents and introducing a second round of bidding. In fact, the mechanism consists of several rounds of two-bidders, single-unit second-price auctions similar to those of the VCGm. As these second round bids depend on the information of the initial bids of the other agents, it is possible to create an ex-post efficient allocation for a multi-unit auction with bidders having interdependent values.

Besides the group of static auctions, the concept of dynamic auctions designed for economic environments with bidders having interdependent values seems to be promising. Ausubel, for instance, proposed in “An Efficient Ascending-Bid Auction for Multiple Objects” a dynamic auction for interdependent-valuation environments (ref. Ausubel, 2004, pp. 1). Although the presented auction requires relatively severe assumptions concerning the buyers’ bidding behavior, it offers interesting insights. The main advantage of dynamic auctions over static auctions is that they do not force the agents to reveal their private information completely. In fact, the auctioneer demands only a finite number of bids from each agent instead of collecting each individual’s valuation function. Consequently, the group of dynamic auctions enables the creation of a detail-free mechanism for interdependent-valuation environments in such a way Wilson requested it.

Certainly, as dynamic auctions have less information available this group of auctions requests regularity conditions to converge. Otherwise, without such regularity conditions, the dynamic auction will not find an equilibrium after a finite number of steps[33]. Ausubel wants to prevent the agent from waiting to bid truthfully until the end of the auction (ref. Ausubel, 2004, p. 9). Therefore, he assumes for the Ascending-Bid Auction each agent to follow an activity rule that specifies that bids have to be monotonically decreasing. In fact, there exist problems for which agents may want to increase their offer according to their true types although the activity rule excludes this bidding behavior (ref. Example 2 in section 3.3). The idea of the Alternating-Price Auction proposed in chapter 3 is to relax Ausubel's activity rule by introducing an assumption that makes a constraint on the aggregate demand.

Since the 1990s the applications of interdependent-valuation auction grew as bigger and bigger auctions were held to sell public goods, such as infrastructure projects or new bandwidth that allow telecommunication companies to enlarge their portfolio (ref. Binmore & Klemperer, 2001 and McAfee, McMillan & Wilkie, 2009). As expectations concerning the economic benefit from sales of e.g. the next generation bandwidth called 3G were extremely high, it is likely that the biddings of the agents are affiliated. The interdependence of the buyers' values is due to the enormous expected prices for the traded goods and the uncertainty about the de facto economic benefit that will be become apparent only years after the auction. As a consequence, the fear of overpaying brings the agents to include the information they can get from their opponents' values in their own bidding strategy. Hence, the development of auction designs that achieve ex-post efficient allocation even if the buyers' valuations are interdependent is highly relevant.

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[33] In fact, if complete and perfect information could be supposed agents have an optimal strategy to finish the auction quickest possible, just as in the Rubinstein-bargaining-model. For the two-bidders Ascending-Price Auction with complete and perfect information the auction ends after two rounds. The optimal strategy for the first agent is to offer a bid that is acceptable for the second agent just in the first round (ref. Ausubel & Schwartz, 1999, p. 11).

In this chapter a dynamic auction is presented that expands the concept of Ausubels Ascending-Bid Auction by using an alternating-price rule instead of monotonically increasing the trading price in each round. Consequently, the concept of the proposed Alternating-Price Auction that follows the concepts of the Walrasian tatonnement is to enclose an optimal trading price in a way that the resulting allocation is incentive compatible, individually rational and ex-post efficient. In addition, the Alternating-Price Auction needs less information from the buyers compared to known static auctions as it only asks the agents to reveal their bids along the path to the identified optimal allocation. Furthermore, the agents also receive information about their opponents' bids after the end of each round. Therefore, this concept appears more transparent and fairer.

Thus, in the following section 3.2 the chapter starts with defining the setting of environments with buyers having interdependent values. Afterwards, the desired properties incentive compatibility, individual rationality and ex-post efficiency are discussed. In section 3.3 the structure of the Alternating-Price Auction is introduced. Finally, the convergence criteria and the properties of the Alternating-Price Auction are proved and discussed in the sections 3.4 and 3.5.

3.2. Setting of an interdependent-valuation environment

Before starting to explain the Alternating-Price Auction, it is convenient to introduce the setting of interdependent-valuation environments this paper focuses on. First of all, the economic environment consists of $n \in \mathbb{N}, n \geq 2$ different buyers $b_i \in B, i = 1, \dots, n$ that participate in a multi-unit, one-sided auction. Consequently, each buyer is given the opportunity to buy a subset of the $g \in \mathbb{R}_+$ identical copies of one type of good the auctioneer puts up for sale.

The individual demand of each buyer $b_i, i = 1, \dots, n$ is expressed by the real value $d_i \in \mathbb{R}_+$. In interdependent-valuation environments the valuation of a single buyer does not inevitably depend solely on her individual demand, but may also depend on the demands of her opponents. Therefore, the valuation of buyer $b_i, i = 1, \dots, n$ is a function of all buyers' individual demands, i.e. it is defined as the function $v_i: D \to \mathbb{R},\ i = 1, \dots, n$ with the real-valued vector $D = (d_1, \dots, d_n)$ containing all buyers' demands.

In addition to the individual valuation function of all agents, the buyers' utilities also depend on the market price $p \in \mathbb{R}_+$. If it is assumed that buyers have quasi-linear utilities[34], the utility function of every buyer $b_i, i = 1, \dots, n$ can be described by

$$u_i(d_i, d_{-i}, p) = v_i(d_i, d_{-i}) - d_i \cdot p.^{35} \tag{3.1}$$

In case buyer $b_i \in B$ requests no goods, i.e. $d_i = 0$, the utility should equal zero, i.e. participating in the one-sided auction does not present an effort. Thus, it is assumed that the utility of each buyer $b_i \in B$ equals zero, if she requests no goods irrespective of the other buyers' demands, i.e.

$$v_i(0, d_{-i}) = 0 \quad \forall\, i = 1, \dots, n. \tag{3.2}$$

Taking into account the market price announced by the auctioneer, each agent is given the chance to consider her information about the demand of the other buyers and to proclaim her individual demand consistent to her individual values and the information about the other buyers' demands.

Furthermore, this bidding strategy is defined by

$$\rho_i(u_i, d_i, d_{-i}, p) \tag{3.3}$$

for each buyer $b_i, i = 1, \dots, n$.

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[34] A natural assumption for the utility of rational individuals is that effort and earnings of can be separated from each other. Therefore, individual utilities are considered to be quas this paper.

(3.4)

[35] The index $-i$ is used to specify the indices unequal to $i \in I$, i.e. $-i := I \backslash i = \{1, \dots, n\} \backslash i$.

Assuming the agents are interested in maximizing their outcome, the bidding strategy can be expressed by

$$\rho_i(u_i, d_i, d_{-i}, p) \coloneqq \underset{d_i}{\operatorname{argmax}}\, u_i(d_i, d_{-i}, p).$$ [36]

A basic assumption for the auction is that there is competition for every unit of the good the auctioneer wants to sell. Consequently, it is assumed that there exists a price $p_{min} > 0$ for which the demand exceeds the supply, i.e.

$$\sum_{i=1}^{n} \rho_i(u_i, d_i, d_{-i}, p_{min}) > g \ \ \forall\, D. \tag{3.5}$$

Additionally, it is assumed that there exists a price p_{max} with $p_{min} < p_{max} < \infty$ for which the supply exceeds the demand, i.e.

$$\sum_{i=1}^{n} \rho_i(u_i, d_i, d_{-i}, p_{max}) < g \ \ \forall\, D. \tag{3.6}$$

Obviously, assumptions (3.5) and (3.6) are necessary in order to ensure that there exists a trading price that balances out demand and offer.

In the Alternating-Price Auction (APA) the auctioneer adjusts the trading price according to the buyers' demands of the previous round. In order to ensure the convergence of the APA, it is necessary to have a good estimation of how the sum of the buyers' demand changes in consideration of the proposed new trading price. Naturally, it is likely that the overall demand increases if the market price declines, and decreases if the market price rises.

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[36] The properties of the Alternating-Price Auction (APA) do not depend on the concrete formulation of the bidding strategy.

As a consequence, it is assumed that:

If the market price increases, the sum of the buyers' demand decreases, i.e.

$$\sum_{i=1}^{n} \rho_i\left(u_i, d_i\ , d_{-i}, \bar{p}\right) \geq \sum_{i=1}^{n} \rho_i\left(u_i, d_i\ , d_{-i}, \tilde{p}\right)\ \ if\ \ \bar{p} < \tilde{p};\ \bar{p}, \tilde{p} \in \mathbb{R}_+ . \tag{3.7}$$

If the market price decreases, the sum of the buyers' demand increases, i.e.

$$\sum_{i=1}^{n} \rho_i\left(u_i, d_i\ , d_{-i}, \bar{p}\right) \leq \sum_{i=1}^{n} \rho_i\left(u_i, d_i\ , d_{-i}, \tilde{p}\right)\ \ if\ \ \bar{p} > \tilde{p};\ \bar{p}, \tilde{p} \in \mathbb{R}_+ . \tag{3.8}$$

Furthermore, it is necessary to limit the dependence of the utility functions on the opponents' demands. This assumption is required to ensure that the auction converges to an equilibrium. Otherwise, if the dependence on the opponents' demands is not limited appropriately, the agents will want to change their bidding after the end of the APA. Hence, the strategy functions have to be more sensitive to changes of the individual demand than to changes of the demand of the other agents:

$$\left|\rho_i\left(u_i\left(\bar{d}, \bar{d}_{-i}, p\right)\right) - \rho_i\left(u_i\left(\hat{d}, \hat{d}_{-i}, p\right)\right)\right| \leq L \cdot \left\|\bar{D} - \widehat{D}\right\|_1 \tag{3.9}$$

with $0 \leq L < 1.$ [37]

Remark: In fact, assumption (3.9) can be relaxed so that the set of inequalities has to be true after a finite number of steps. In other words, the dynamic auction APA converges if – after an initial phase of bidding – the agents' response function depends more on the own than on the opponents's changes in bids. For the sake of simplicity and without loss of generality it is assumed that (3.9.) has to be satisfied throughout the auction. ■

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[37] $\|x\|_1$ labels the 1-norm which is used as vector norm in this paper. The 1-norm is defined as $\|x\|_1 = \sum |x_i|$.

In addition to (3.2), it is assumed that the buyers only trade if their revenue is strictly positive, i.e.

$$\rho_i(0) = 0 \quad \forall i = 1, \dots, n. \tag{3.10}$$

3.3. Concept of the Alternating-Price Auction (APA)

In summary, the main idea of the Alternating-Price Auction is to install an enclosure algorithm for the market price that converges to a price which corresponds to an ex-post efficient allocation. Therefore, the auctioneer announces a trading price $p^l \in \mathbb{R}_+$ and afterwards reveals the referring bids of all buyers[38]. After each buyer has reconsidered her bid, having the information of the previous rounds of bidding, the next price is made known and again the agents are asked to send their bids to the auctioneer.

Remembering that the auctioneer wants to sell exactly $g \in \mathbb{N}$ goods, it is obvious that the sum of the buyers' optimal demands has to equal the number of available goods, i.e.

$$\sum_{i=1}^{n} d_i^* = g. \tag{3.11}$$

Consequently, the iteration has to be repeated until condition (3.11) is satisfied. The goal is to reduce the difference between the buyers' demand and the number of available goods by each step of the iteration.

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[38] The index $l \in \mathbb{N}_+$ labels the actual step of the iteration.

Hence, the auction shall ensure the convergence conditions

$$\lim_{l \to \infty} p^l = p^*, p^* \in \mathbb{R}_+ \tag{3.12}$$

for the price sequence and

$$\lim_{l \to \infty} \sum_{i=1}^{n} d_i^l = g \tag{3.13}$$

for the sequence of the buyers' demands.

Obviously, the price has to be adjusted according to the actual deviation between the buyers' demand and the number of available goods. If the buyers' demand is unequal to the number of available goods, the price has to be modified according to the following rule, which is a consequence of conditions (3.7) and (3.8):

If

$$\sum_{i=1}^{n} d_i^l > g$$

the price has to be increased, i.e. $p^{l+1} > p^l$.

If

$$\sum_{i=1}^{n} d_i^l < g$$

the price has to be decreased, i.e. $p^{l+1} < p^l$.

The concept of the APA is to increase the price when the demand of the buyers exceeds the number of available goods and vice versa.

Consequently, it is necessary to start the iteration with a pair of prices p_{min} and p_{max} that ensure the enclosure criteria (3.5) and (3.6):

$$p_{min}\colon \sum_{i=1}^{n} \rho_i(u_i, d_i, d_{-i}, p_{min}) > g \ \ \forall\, D \tag{3.14}$$

and

$$p_{max}\colon \sum_{i=1}^{n} \rho_i(u_i, d_i, d_{-i}, p_{max}) < g \ \ \forall\, D.$$

After this initial phase, the auctioneer starts the iteration consisting of several rounds of announcing a price and afterwards revealing the buyers' bids. The APA is formulated as follows.

Definition of the Alternating-Price Auction (APA)

(i) The iteration starts with the initial prices $p_o = p_{max},\ p_1 = p_{min}$ that are chosen by the auctioneer according to condition (3.14) for p_{min} and respectively for p_{max}.

(ii) $l = 1$

Choose $\delta, \varepsilon \in \mathbb{R}_+$ for the abort criteria of the auction.

```
While $\left| \left\| \sum_{i=1}^{n} d_i^l \right\|_1 - g \right| > \delta$ and $|p^l - p^{l-1}| > \varepsilon$
    $l = l + 1$
    a) If $\sum_{i=1}^{n} d_i^l > g$ and $\sum_{i=1}^{n} d_i^{l-1} \le g$
        Then the new trading price is computed by
        $p^{l+1} = \frac{1}{2}(p^l + p^{l-1})$.
```

```
            b) Else If $\sum_{i=1}^{n} d_i^l \leq g$ and $\sum_{i=1}^{n} d_i^{l-1} > g$
                  Then the new trading price is computed by
                  $p^{l+1} = \frac{1}{2}(p^l + p^{l-1})$.

            c) Else If $\sum_{i=1}^{n} d_i^l > g$ and $\sum_{i=1}^{n} d_i^{l-1} > g$
                  Then the new trading price is computed by
                  $p^{l+1} = 2 \cdot p^l - p^{l-1}$.

            d) Else If $\sum_{i=1}^{n} d_i^l \leq g$ and $\sum_{i=1}^{n} d_i^{l-1} \leq g$
                  Then the new trading price is computed by
                  $p^{l+1} = 2 \cdot p^l - p^{l-1}$.

               End If

            The auctioneer proclaims the new price $p^{l+1}$ and in addition the
            demands $D^l = \left(d_j^l\right)_{j=1,\dots,n}$ from the previous round.

            Afterwards, the buyers $b_i, i = 1, \dots, n$ are asked to send their
            individual demands

                        $d_i^{l+1} = \rho_i\left(u_i, d_{-i}^l, p^{l+1}\right)$

            consistent with the price $p^l$ and the other buyers' demands of the
            round before.

      End While

   (iii) Finally, the optimal allocation is defined by $D^* = D^l$
         and the price $p^* = p^l$.
```

Next, two examples are presented in order to illustrate how the APA works. In addition, it is explained why the assumptions made in section 3.2 are needed to ensure the convergence of the APA.

Example 1

First, a two-buyers auction is studied where the agents have the following utility functions

$$u_1 = \left(d_2\right)^2 \cdot d_1 - p\, d_1$$

for buyer b_1 and

$$u_2 = \left(d_1\right)^2 \cdot d_2 - p\, d_2$$

for buyer b_2. It is assumed that the auctioneer wants to sell $g = 10$ identical copies of one good.

Obviously, condition (3.9) is not satisfied, i.e. the agents' utilities depend more on their opponents' than on their own demand. As a consequence the bidding strategies will oscillate between 0 and 10 and the APA does not converge to an equilibrium.

Results of the APA for example 1:

l	p^l	d_1^l	d_2^l	$\left\|\sum_{i=1}^{n} d_i^l\right\|_1 - g$	$\left\|p^l - p^{l-1}\right\|$
1	0.00000	10.00000	10.00000	10.00000	0.00000
2	1000.00000	0.00000	0.00000	- 10.00000	1000.00000
3	500.00000	0.00000	0.00000	- 10.00000	500.00000
4	0.00000	10.00000	10.00000	10.00000	500.00000
5	250.00000	0.00000	0.00000	- 10.00000	250.00000
6	125.00000	0.00000	0.00000	- 10.00000	125.00000
7	0.00000	10.00000	10.00000	10.00000	125.00000
8	62.50000	0.00000	0.00000	- 10.00000	62.50000
9	31.25000	10.00000	0.00000	0.00000	31.25000
10	0.00000	10.00000	10.00000	10.00000	31.25000
11	15.62500	0.00000	0.00000	- 10.00000	15.62500
12	7.81250	10.00000	10.00000	10.00000	7.81250
13	11.71875	0.00000	0.00000	- 10.00000	3.90625
14	9.76563	10.00000	10.00000	10.00000	1.95313
15	10.74219	0.00000	0.00000	- 10.00000	0.97656
…	…	…	…	…	…

…	…	…	…	…	…
30	3.41797	0.00000	10.00000	0.00000	0.48828
31	2.92969	0.00000	0.00000	- 10.00000	0.48828
32	2.44141	10.00000	0.00000	0.00000	0.48828
33	1.95313	0.00000	0.00000	- 10.00000	0.48828
34	1.46484	0.00000	10.00000	0.00000	0.48828
35	0.97656	0.00000	0.00000	- 10.00000	0.48828
36	0.48828	10.00000	0.00000	0.00000	0.48828
37	0.00000	10.00000	10.00000	10.00000	0.48828
38	0.24414	0.00000	10.00000	0.00000	0.24414
39	0.12207	10.00000	10.00000	10.00000	0.12207
40	0.18311	10.00000	0.00000	0.00000	0.06104
…	…	…	…	…	…

■

Example 2

In order to highlight the differences between the Ascending-Bid Auction and the Alternating-Price Auction, an example is presented in which $g = 7$ identical copies of one good are put up for sale in a two-buyers auction. The individual utility functions are

$$u_1 = 0.3\, d_1 + 0.1\, d_1 \sqrt{d_2} - p\, d_1$$

for buyer b_1 and

$$u_2 = 0.8\, d_2 - 0.1 \sqrt{d_1}\, d_2 - p\, d_2$$

for buyer b_2.

First of all, the results of the Ascending-Bid Auction are studied. At a trading price $p = 0.54$ the Ascending-Bid Auction stops as the demand of buyer b_2 equals zero. Consequently, the goods are allocated to b_1 at a price of $p = 0.54$. However, if b_2 was given the chance to reconsider her bid, she would subsequently increase her demand. Indeed, the utility functions of this example violate the assumption of monotone bidding the Ascending-Bid Auction presumes.

Results of the Ascending-Bid Auction for example 2:

l	p^l	d_1^l	d_2^l	$\left\|\sum_{i=1}^{n} d_i^l\right\|_1 - g$
0	0.00	7.0	7.0	7.0
1	0.01	7.0	7.0	7.0
2	0.02	7.0	7.0	7.0
…	…	…	…	…
53	0.53	7.0	7.0	7.0
54	0.54	7.0	7.0	7.0
55	0.55	7.0	0.0	0.0
56	0.56	0.0	0.0	-7.0
57	0.57	0.0	7.0	0.0
58	0.58	0.0	7.0	0.0
59	0.59	0.0	7.0	0.0
…	…	…	…	…
77	0.77	0.0	7.0	0.0
78	0.78	0.0	7.0	0.0
79	0.79	0.0	7.0	0.0
80	0.80	0.0	7.0	0.0
81	0.81	0.0	7.0	-0.0
82	0.82	0.0	0.0	-7.0
…	…	…	…	…
99	0.99	0.0	0.0	-7.0
100	1.00	0.0	0.0	-7.0

By contrast, the Alternating-Price Auction allows the buyers to consider the biddings of their opponents and to increase or decrease their demand for the next round of the auction. The assumption of monotone bidding is replaced by (3.7) and (3.8) that focus on the common bidding behavior instead of that of the individuals.

If the APA is carried out with $\delta = 0.0001$ and $\varepsilon = 0.01$, the iteration terminates after 31 steps. All of the goods are allocated to b_2 at a price of $p = 0.53101$.

Results of the APA for example 2:

l	p^l	d_1^l	d_2^l	$\left\|\sum_{i=1}^{n} d_i^l\right\|_1 - g$	$\left\|p^l - p^{l-1}\right\|$
1	0.00000	7.00000	7.00000	7.00000	0.00000
2	100.00000	0.00000	0.00000	-7.00000	100.00000
3	50.00000	0.00000	0.00000	-7.00000	50.00000
4	0.00000	7.00000	7.00000	7.00000	50.00000
5	25.00000	0.00000	0.00000	-7.00000	25.00000
6	12.50000	0.00000	0.00000	-7.00000	12.50000
7	0.00000	7.00000	7.00000	7.00000	12.50000
8	6.25000	0.00000	0.00000	-7.00000	6.25000
9	3.12500	0.00000	0.00000	-7.00000	3.12500
10	0.00000	7.00000	7.00000	7.00000	3.12500
11	1.56250	0.00000	0.00000	-7.00000	1.56250
12	0.78125	0.00000	0.00000	-7.00000	0.78125
13	0.00000	7.00000	7.00000	7.00000	0.78125
14	0.39063	0.00000	7.00000	0.00000	0.39063
15	0.19531	7.00000	7.00000	7.00000	0.19531
16	0.29297	7.00000	7.00000	7.00000	0.09766
17	0.39063	7.00000	7.00000	7.00000	0.09766
18	0.48828	7.00000	7.00000	7.00000	0.09766
19	0.58594	0.00000	0.00000	-7.00000	0.09766
20	0.53711	7.00000	0.00000	0.00000	0.04883
21	0.48828	0.00000	7.00000	0.00000	0.04883
22	0.43945	0.00000	7.00000	0.00000	0.04883
23	0.39063	7.00000	7.00000	7.00000	0.04883
24	0.41504	7.00000	7.00000	7.00000	0.02441
25	0.43945	7.00000	7.00000	7.00000	0.02441
26	0.46387	7.00000	7.00000	7.00000	0.02441
27	0.48828	7.00000	7.00000	7.00000	0.02441
28	0.51270	7.00000	7.00000	7.00000	0.02441
29	0.53711	7.00000	0.00000	0.00000	0.02441
30	0.52490	7.00000	7.00000	7.00000	0.01221
31	0.53101	0.00000	7.00000	0.00000	0.00610

■

3.4. Characteristics of the Alternating-Price Auction (APA)

As mentioned in the introduction, there are static auctions for interdependent-valuation environments that are incentive compatible, individually rational and ex-post allocative efficient without strong assumption concerning the buyers' valuation functions. On the other hand, these concepts require complete information from the agents to compute an efficient allocation. Consequently, the idea of this paper is to introduce a multi-unit auction for interdependent-valuation environments that also achieves incentive compatibility, individual rationality and ex-post allocative efficiency, but at the same time is less complex. Indeed, the main aspect of the Alternating-Price Auction is that less individual information is required to find an appropriate allocation. As a result, the proposed mechanism appears more transparent and fairer to the bidders.

In example 2 the APA achieves an incentive compatible and ex-post efficient allocation. Finally, it is left open to prove the properties of the APA in general considering the assumptions made in section 3.2.

First, it is necessary to examine whether the APA converges if assumptions (3.5) – (3.8) are true. As discussed in section 3.3, the idea of the APA is that the market price converges, and at the same time the sum of the buyers' demand converges to the supply.

In order to converge to a fixed trading price, it is essential that the APA satisfies the convergence criteria

$$|p^{l+1} - p^{l}| \leq |p^{l} - p^{l-1}| \tag{3.15}$$

and

$$|p^{l+1} - p^{l}| \xrightarrow{l\to\infty} 0. \tag{3.16}$$

Proposition 3.1: The multi-unit auction APA proposed in section 3.3 satisfies conditions (3.15) and, in addition, (3.16).

Proof: In order to prove (3.15), it is necessary to investigate each case of step (ii) of the APA separately.

a), b) $|p^{l+1} - p^l| = \left|\frac{1}{2}(p^l + p^{l-1}) - p^l\right| = \left|\frac{1}{2}p^{l-1} - \frac{1}{2}p^l\right|$

$= \frac{1}{2}|p^{l-1} - p^l| < |p^{l-1} - p^l|$

c), d) $|p^{l+1} - p^l| = |2 \cdot p^l - p^{l-1} - p^l| = |p^l - p^{l-1}|$

As a consequence, $|p^{l+1} - p^l| \leq |p^{l-1} - p^l|$ is satisfied.

As a summary, the APA of section 3.3 satisfies condition (3.15), i.e. the series of the price differences $|p^{l+1} - p^l|$ is monotonically decreasing. Furthermore, it is necessary to show that (3.16) is true, too.

If one considers assumptions (3.5) and (3.6), then there exist an upper and a lower bound of the market price. Therefore, it is ensured that after a finite number of iterations the new price is built according to case a) or case b) of step (ii), i.e. $|p^{l+1} - p^l| < |p^l - p^{l-1}|$. As a consequence, the series of the price differences $|p^{l+1} - p^l|$ converges to 0 if $l \to \infty$. □

Proposition 3.2: For each pair of $\delta, \varepsilon \in \mathbb{R}_+$ there exists a $l > 1$ that satisfies

$$\left|\sum_{i=1}^{n} d_i^l - g\right| = 0$$

with $\|D^l - D^{l-1}\| < \delta$ and $|p^l - p^{l-1}| < \varepsilon$.

Proof: Considering proposition 3.1, it is clear that there exists a $l > 1$ for which $|p^l - p^{l-1}| < \varepsilon$. It follows from assumptions (3.7) to (3.9) that changes of the demand functions vanish if $|p^l - p^{l-1}| \xrightarrow{l\to\infty} 0$.

In addition, it is ensured that there exists an index $l > 1$ for which $\sum_{i=1}^{n} d_i^l$ equals the limit from the left due to condition (3.10). Taking into consideration that the mechanism encloses the equilibrium price by each step of the iteration, it follows from (3.9) and the Banach fixed point theorem that even $\left|\sum_{i=1}^{n} d_i^l - g\right| = 0$ for a $l > 1$. □

Proposition 3.3: The APA is incentive compatible and individually rational.

Proof: First, the individual rationality of the dynamic auction APA is ensured because trades are only carried out after the agents place a bid. As a result, each agent only trades if she expects positive revenue at the announced trading price. Consequently, the agents' expected outcome of the dynamic auction APA is non-negative, i.e. the mechanism is individually rational.

As the found allocation D^* satisfies condition (3.12) and in addition condition (3.13), the APA ensures that $\rho_i(u_i, d_i^*, d_{-i}^*, p^*) \quad \forall i = 1, \ldots, n$. As a consequence, the APA is incentive compatible. □

3.5. Discussion of the properties of the Alternating-Price Auction (APA)

In recent years several interesting concepts were developed that deal with achieving ex-post efficient allocations in interdependent-valuation environments. This chapter proposes a dynamic auction that is based on the idea of enclosing the trading price. The concept of announcing a certain price and revealing the accompanying bids limits the information that is needed compared to well-known existing static auctions. Indeed, the Alternating-Price Auction (APA) collects only a finite number of biddings instead of accumulating the complete valuation function from every buyer. Furthermore, each buyer receives transparency about the bids of her opponents. Although the APA is less complex, it provides the important properties individual rationality, incentive compatibility and ex-post allocative efficiency.

Compared to Ausubels Ascending-Bid Auction, the APA needs less severe assumptions concerning the buyers’ bidding behavior. In fact, the convergence criterion of the Ascending-Bid Auction depends on the assumption that the biddings have to be monotonically decreasing throughout the auction. As a consequence, there exist economic environments for which the Ascending-Bid Auction fails to achieve an ex-post efficient allocation (ref. Example 2 in section 3.3). As a summary, the APA enlarges the existing approaches of dynamic auctions for interdependent-valuation environments.

4. Facilitating Short-Term and Long-Term Efficiency with an Integrated Electricity Market Design

Abstract

An electricity market design is introduced that focuses on building an integrated market for energy supplies by considering all relevant participants. More precisely, producers and consumers of electric energy are part of the market design as well as investors and service providers of the transmission network.

The main aspect of the integrated market is to overcome the free-riders problem that arises when investments in network capacities have to be averaged. A main idea of the proposed electricity market design is to make use of known techniques of optimal flow problems. Therefore, the efficient development of transport capacities is facilitated while, at the same time, short-term allocative efficiency is ensured if transport capacities are sufficient.

4.1. Introduction into electricity market designs

Considering the modeling of electricity markets, it is inevitably to be aware of the main features that distinguish power trades from other markets. Unlike other commodities, the trade of electricity, gas or water requires an adequate network to directly connect buyers and sellers. Taking into consideration that these network capacities are durable, immovable and expensive, a main task in energy supply is the precise controlling of investments in transmission capacities. Another aspect of electric energy is that excess production cannot be stored in large amounts due to insufficient and very costly capacities. As a consequence, production and consumption of electricity at a certain period of time are directly linked. Finally, demand of electric energy fluctuates over time and is difficult to predict. As a summary, some inefficiency in electricity markets are inevitable due to the fact that energy flow cannot be perfectly observed and storage capacities are strongly limited (Wilson, 2002, pp. 1300). Especially changes of the demand in between a short time frame cause highly remarkable costs for providing the additional production capacity.

As one considers the creation of electricity market design, two main tasks have to be addressed. First, there is the problem of supporting the entry of sufficient investments into network and production capacities and second, there is the problem of dealing with market power that leads to incentive incompatibilities in energy markets.

In addition, it is inevitable to consider the fact that power markets generally consist of a small number of large producers that supply the demand. Consequently, designers of electricity auctions are faced with the problem of bidding reduction in order to influence the trading price (ref. Ausubel & Cramton, 2002). Large market participants could be tempted to abstain from the trade of the last goods in order to manipulate the price according to their individual interests.

Beside the classical requirements that energy supply has to be reliable and cost efficient, the need for sustainable production and transportation of electricity is getting more important (ref. European Commission, 2012). The issue of changing electricity markets towards a sustainable energy supply – one of the crucial questions to be answered in the near future – increases the requirement of a suitable concept to integrate the development of transport network into the process of electricity allocation.

As one regards the increasing demand for electricity and, in addition, further developments in network capacities, conventional concepts that are based on central planning or stringent regulation fail to achieve the necessary effectiveness. Considering, on the one hand, the financial requirements that are needed in order to improve network capacities and, on the other hand, the limited governmental budgets, the question arises how to encourage private financiers to invest in additional capacities of the transport network. Existing electricity markets are sometimes afflicted by the absence of incentives for private financiers to invest in the transport network (Abdala and Chambouleyron, 1999, p.1) due to stringent regulation regarding the allocation of network capacities. Consequently, there is a discussion whether market-based mechanisms could provide better solutions to the problem of energy supply or if stringent regulation is needed in order to achieve an affordable, dependable and sustainable electricity market. It is expected that market-based power trades lead to a higher output, lower wholesale prices and better service quality throughout the energy supply chain.

On the one hand, perfect competition offers a more comprehensive solution to the issue of allocating electric energy than concepts with centrally planned prices. Considering Newbery (ref. Newbery, 2003, p. 4), the inefficiency of markets with regulatorily defined prices is highly evident. On the other hand, market-based concepts are vulnerable to market power, necessitating regulatory elements (ref. Meeus, 2010, p. 5).

Considering California's electricity crises at the beginning of this century when electricity costs increased tenfold within a few month, it became traceable that deregulation and the presence of market power could lead to enormous imbalance in power markets (ref. Borenstein, 2002, p. 191). In 2001 the price development of electricity exchanges and the bankruptcy of large consumers forced the state of California to intervene into power markets by buying power. Beside market power in deregulated markets, observers of the power crises in California suggest that the absence of sufficient long-term contracts had advantaged the price development (ref. Borenstein, 2002, pp. 201). As mentioned above, the demand of electric energy is highly volatile although there exist predictable and dependable seasonal components that can be used to partly accommodate the demand by using long-term contracts. Consequently, short-term changes of energy demand that inevitably lead to inefficiencies could be restrained by short-term contracts as day-ahead or intra-day auctions.

Nowadays, most industrialized countries have implemented auction designs to organize the trade of their power markets adequately according to seasonal aspects. Generally, the totality of a power market is separated into a long-term auction that manages the basement supply that is constant in the long-run, and into day-ahead and intra-day trading that compensate the short-term changes in demand[39].

Faced with the lack of investment in transmission capacities that limit the options for power exchange throughout a coherent market, an interesting approach to deal with these insufficiencies of network capacities was developed by Bjørndal and Jørnsten. The authors proposed an electricity auction design that is based on the division into a finite number of separate energy markets, whereby long-distance power trades are reduced to manage on limited network capacities (ref. Bjørndal & Jørnsten, 2001). Indeed, the fact that individual information about energy demand and supply, in addition to the existing network capacities, are used to define the optimal number and size of the several zones induces conflicting interests that result in additional incentive incompatibilities in power trades. As a consequence, a concept of the Integrated Electricity Market Design proposed subsequently is to install a mechanism that finances production and development of network capacity by putting together including all relevant participants of energy trades.

Surely, the lack of investments in adequate capacities of generators and transmission networks is a negative effect of market power in electricity auctions. By deregulating the energy supply, governments put the responsibility of installing sufficient capacities for production and transportation of electricity in the hands of the market itself. In regulated power markets a central authority manages to encourage energy suppliers and network providers to invest in generators and networks to meet future demand. Following economic theory (ref. Vázquez &

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[39] Currently, energy exchange companies provide a huge variety of power trade derivatives differing in the duration of contract (ref. e.g. the European Energy Exchange, 2013).

Rivier & Pérez-Arriaga, 2002, p.1), there are difficulties that prevent free markets from providing a sufficient, long-term-secure energy supply. First of all, although the investment in additional generators or network capacities is economically justified, agents may avoid the risky speculation. Even if the expected income for peaking demand is high, risk-averse agents may tend to decline to invest and may prefer the secure revenue of short-term demand. Second, market power generally creates incentive to influence the price by reducing either demand or offer (ref. Ausubel & Cramton, 2002). This problem also prevents oligopolists in power markets from investing in generator or network capacities in order to increase the price for future trades.

Vázquez, Rivier and Pérez-Arriaga developed an auction that allocates long-term reliability contracts to secure future energy supply. In fact, market participants bid on financial call options for long-term power trades with costly penalties for non-delivery (ref. Vázquez & Rivier & Pérez-Arriaga, 2002, p. 6). However, the proposed market for long-term security does not encourage the agents to participate without regulatory intervention.

In the short run, the aspect of affordable energy is of priority. Therefore, the short-term efficiency is similar to the concept of allocative efficiency, i.e. the maximization of the overall gains from trade. By contrast, long-term efficiency is defined as the maximization of future gains from energy trades, i.e. it requires to minimize the necessary investments and operating costs for the future transmission network. Taking into consideration that it is necessary to invest into network capacities in order to conserve and partly to enlarge the network, it is obvious that in the long run also future efficiency properties have to be regarded (ref. De Vries & De Joode & Hakvoort, 2009, p. 3).

Besides efficiency, the free-riders problem which constitutes a fair share of the cost for the network, is essential in electricity market design. As the costs in increasing the network capacities are high, the core question is how to ensure a reliable refinancing that, in addition, provides a fair share of the effort. Existing concepts propose a refinancing of investments that depends on future trading rates. As a consequence, the outcome for the investor is uncertain (ref. Newbery, 2003, p. 4) and may prevent risk-averse investors to enter the market. Hence, in order to remove market entry barriers for potential investors, the investors' future revenues have to be uncoupled from physical transmission of the additional routes.

Certainly, it is an important question how to manage the distribution of physical and financial transmission rights[40]. For instance, Chao, Peck, Oren and Wilson pointed out that centralized markets generally disregard long-term efficiency while focusing on short-term benefits (ref. Chao & Peck & Oren & Wilson, 2000, p. 2). On the contrary, competitive markets for transmission rights could facilitate the effective and efficient usage of existing network utilities while at the same time supporting the adequate development of transmission capacities matching future demand. Besides, there is a scientific skepticism about the practicability of decentralized markets that manage the allocation of transmission rights. In summary, the main arguments against the application of decentralized markets for the sale of transmission rights are the expected complexity of such approaches and the potential vulnerability to market power.

However, the authors propose a congestion management that is based on the installation of separate markets for the allocation of transmission rights, long-term energy trades and short-term energy trades (ref. Chao & Peck & Oren & Wilson, 2000, p. 22). In a first market, transmission rights are allocated to the market participants in annual auctions. Afterwards, there is a secondary market for reselling transmission rights according to the actual trend of demand and supply of power trades. Considering the energy trades, the authors recommend the implementation of known long-term and short-term auction formats.

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[40] Usage rights of network capacity are usually distinguished between physical transmission rights – that enable the holder to use a specific transmission interface – and the financial transmission rights – that give the holder the right on the congestion rent (ref. Joswok & Tirole, 452).

To illustrate, the most important disadvantage of existing energy auction formats is that the applied auction formats do not integrate all relevant market participants. Moreover, Wilson characterizes an integrated electricity market design as “a long-term relational contract among participants, and a smart market that includes overall optimization of operational decisions” (ref. Wilson, 2002, p.1304). As a consequence, in the following chapter an integrated auction design is presented that achieves an individually rational, budget balanced and approximately incentive compatible electricity transmission.

In fact, the electricity design is short-term efficient if investments and operating costs are neglected, and facilitates a long-term efficient development of the transport network. In order to install an aggregate process of financing, production and servicing, a mechanism consisting of two one-sided auction series and one double auction is installed. Governmental regulation is not required for the price definition or the allocation process, but for the establishment of an appropriate economic environment, i.e. transparency about the expected capacities of the electricity network and future electricity production.

4.2. Setting of an electricity market

Subsequently, a mechanism is proposed in which four types of agents participate in the trade of electric energy. For now, it is assumed that each agent can be unambiguously assigned to one of these groups: customers, producers, operators or investors[41]. In this section the mathematical model of the electricity market this paper focuses on is defined.

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[41] The question of whether one agent could act, for instance as a producer and operator at the same time without violating the property of incentive compatibility is addressed in section 4.5.

The group of customers is described by

$$C = \{c_1, \dots, c_k\}. \tag{4.1}$$

Each of the $k \in \mathbb{N}_+$ buyers requests a finite amount of electric energy

$$d_{c_h}^t, h = 1, \dots, k \tag{4.2}$$

in time period $t = 0,1, \dots, \Pi$. Obviously the demand of each consumer may vary over time.

Next,

$$S = \{s_1, \dots, s_n\} \tag{4.3}$$

reflects the energy-producing companies, that provide

$$g_{s_r}^t, r = 1, \dots, n \tag{4.4}$$

units of electric energy in $t = 0,1, \dots, \Pi$.

Remark: It is assumed that demand and offer for the next Π time periods are known to buyers and sellers. Furthermore, the agents are asked to signal their future demand and offer to the auctioneer comparable to existing regulations for market transparency (ref. Verordnung (EG) Nr. 714/2009, 2009).

Due to seasonal variation or the improvement of production capacities, the amount of energy that is produced by a specific producer is variable. This property is considered, as both demand and supply, are functions that depend on time.

The concept of mechanism design presupposes that each agent has got a suggestion to the worth of the good she is going to buy or sell. Of course, this suggestion is private knowledge and does not necessarily have to correspond to the individual information of her opponents.

Similarily, the individual value assigned to one unit of electric energy by consumer $c_h, h = 1, \ldots, k$ is equal to

$$v_{c_h}^t \in \mathbb{R}^+. \tag{4.5}$$

The individual value for one unit of electric energy given by $s_r, r = 1, \ldots, n$ is furthermore described by

$$v_{s_r}^t \in \mathbb{R}^+. \tag{4.6}$$

In contrast to the original design of double auctions in which buyers and sellers trade directly, the trade of electric energy requires network capacities to transport the electricity from the producers to the customers. This paper distinguishes between companies

$$F = \{f_1, \ldots, f_m\} \tag{4.7}$$

that invest in the installation of network capacities, and companies

$$O = \{o_1, \ldots, o_l\} \tag{4.8}$$

that keep the network in working order.

In each period of time $t = 0,1, \ldots, \Pi$ the auctioneer reconsiders the status of the network and finally proposes the investments

$$I^t = \{I_1^t, I_2^t, \ldots\} \tag{4.9}$$

that have to be carried out next. The decision of the auctioneer is based on the public information about the existing capacities of the producers, the network capacities and the prognoses about the future demand[42]. Eventually, the total costs agent $f_j, j = 1, \dots, m$ has to afford in $t = 0,1, \dots, \Pi$ are defined as $a^t_{f_j} \in \mathbb{R}_+$[43].

For the sake of simplicity and without loss of generality it is assumed that the implementation time is constant for each project and equals one time period. For this reason, the additional network capacity is completed in the period after the investment.

Similarly to the investments, the auctioneer also divides the totality of maintenance tasks into well defined service packages

$$U^t = \{U^t_1, U^t_2, \dots\}. \tag{4.10}$$

The total operating expense of company $o_i, i = 1, \dots, l$ in $t = 0,1, \dots, \Pi$ is described by $a^t_{o_i} \in \mathbb{R}_+$.

Moreover, it is necessary to mathematically express the energy flow as the main result of the allocation. The amount of energy seller $s_r,\ r = 1, \dots, n$ delivers to buyer $c_h,\ h = 1, \dots, k$ is described by the real value $q^t_{c_h,s_r} \in \mathbb{R}^+$ and, eventually, all energy trades are summed up in the quantity matrix

$$Q^t = \begin{pmatrix} q^t_{c_1,s_1} & \cdots & q^t_{c_1,s_n} \\ \vdots & \ddots & \vdots \\ q^t_{c_k,s_1} & \cdots & q^t_{c_k,c_n} \end{pmatrix}. \tag{4.11}$$

In order to adequately map the transmission capacities it is necessary to define

$$X = \{x_1, x_2, \dots, x_\alpha\} \tag{4.12}$$

as the set of junction nodes.

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[42] The description of how to select the projects that have to be carried out in the next period of time is part of Example 3 and section 4.5. For now, it is assumed that these investment bundles and operation service packages are known and well defined.

[43] The definition of the prices for investment and maintenance are part of the proposed mechanism (ref. section 4.2 IEMD step 1. And step 2.).

Consequently, it is possible to introduce $w^t_{\lambda,\mu} \in \mathbb{R}_+$ to characterizes the amount of electric energy that can be transmitted from $\lambda \in S, C, X$ to $\mu \in S, C, X$ regarding the transmission capacities at $t = 0,1, \dots, \Pi$. Finally, these transport capacities are combined in the network capacity matrix

$$W^t = \begin{pmatrix} \begin{bmatrix} w^t_{c_1,x_1} & \cdots & w^t_{c_1,x_\alpha} \\ \vdots & \ddots & \vdots \\ w^t_{c_k,x_1} & \dots & w^t_{c_k,x_\alpha} \end{bmatrix} & \begin{bmatrix} w^t_{c_1,s_1} & \cdots & w^t_{c_1,s_n} \\ \vdots & \ddots & \vdots \\ w^t_{c_k,s_1} & \dots & w^t_{c_k,s_n} \end{bmatrix} \\ \begin{bmatrix} w^t_{x_1,x_1} & \cdots & w^t_{x_1,x_\alpha} \\ \vdots & \ddots & \vdots \\ w^t_{x_\alpha,x_1} & \dots & w^t_{x_\alpha,x_\alpha} \end{bmatrix} & \begin{bmatrix} w^t_{x_1,s_1} & \cdots & w^t_{x_1,s_n} \\ \vdots & \ddots & \vdots \\ w^t_{x_\alpha,s_1} & \dots & w^t_{x_\alpha,s_n} \end{bmatrix} \end{pmatrix}. \tag{4.13}$$

The corresponding cost for transportation are defined as $y^t_{\lambda,\mu} \in \mathbb{R}_+$ for the transmission from $\lambda \in S, C, X$ to $\mu \in S, C, X$ regarding the transmission capacities at $t = 0,1, \dots, \Pi$.[44] Similarly, these transport costs are combined in the network capacity matrix

$$Y^t = \begin{pmatrix} \begin{bmatrix} y^t_{c_1,x_1} & \cdots & y^t_{c_1,x_\alpha} \\ \vdots & \ddots & \vdots \\ y^t_{c_k,x_1} & \dots & y^t_{c_k,x_\alpha} \end{bmatrix} & \begin{bmatrix} y^t_{c_1,s_1} & \cdots & y^t_{c_1,s_n} \\ \vdots & \ddots & \vdots \\ y^t_{c_k,s_1} & \dots & y^t_{c_k,s_n} \end{bmatrix} \\ \begin{bmatrix} y^t_{x_1,x_1} & \cdots & y^t_{x_1,x_\alpha} \\ \vdots & \ddots & \vdots \\ y^t_{x_\alpha,x_1} & \dots & y^t_{x_\alpha,x_\alpha} \end{bmatrix} & \begin{bmatrix} y^t_{x_1,s_1} & \cdots & y^t_{x_1,s_n} \\ \vdots & \ddots & \vdots \\ y^t_{x_\alpha,s_1} & \dots & y^t_{x_\alpha,s_n} \end{bmatrix} \end{pmatrix}. \tag{4.14}$$

Remark: To simplify the mathematical model of the electricity market design some physical characteristics of power transmissions are neglected. First, it is assumed that there is no loss of electric energy due to transmission.

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[44] The IEMD is free to use any function Y that assigns costs to every branch of the network. As a consequence, the auctioneer could use either the actual investments and service fees or could choose another approach to quantify the transport costs.

Second, Kirchhoff's circuit laws explain basic physical rules for electric engineering in transmission networks. The first Kirchhoff law implies that the sum of power flows into a junction equals the power flows from the same junction. By using the techniques of network flow patterns this characteristic is satisfied by the Integrated Electricity Market Design (IEMD). Furthermore, Kirchhoff's second law indicates that the voltage around a closed loop sums up to zero.

For now, it is assumed that the distribution of electric energy is lossless and that Kirchhoff's second law can be neglected. Feasible enhancements of the IEMD in order to ensure both characteristics are discussed in section 4.5. ■

After finishing the mathematical description of the economic environment, this paper focuses on formulating the assumptions that have to be satisfied in order to ensure the expected properties of the auction. As mentioned above, the reliable supply of electric energy is an important property for electricity markets. Consequently, it is assumed that the producers $S = \{s_1, \dots, s_n\}$, as well as the network service providers $O = \{o_1, \dots, o_l\}$, have adequate reserves to accommodate the demand in each period of time $t = 0,1, \dots, \Pi$.

Therefore, it is assumed that

$$\sum_{r=1}^{n} g_{s_r}^{t} > \sum_{h=1}^{k} d_{c_h}^{t} + R_e, \ \ t = 0,1, \dots, \Pi \tag{4.15}$$

i.e. that the supply exceeds the demand in each period of time[45].

Furthermore, the transport capacities for electric energy have to be sufficient so that each consumer has the chance to receive the required amount of electricity. Considering that the concept of the proposed auction is to refinance the costs of

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[45] To simplify the mathematical formulation, the reserve constants are fixed in this paper. It is also possible to install a net reserve that changes in time according to the uncertainty about the prognoses of supply and demand.

expanding and operating the network, it is obvious that one part of the price per unit of electric energy refers to these tasks. Second, it is necessary to consider the costs that arise from producing electric energy at the power plants. As mentioned above, the idea of this paper is to install a price per unit of electric energy – henceforth defined as $p \in \mathbb{R}_+$ – that is the same for each participant in the auction and constant for each unit of electric energy that is traded. The concept is to add a portion of the costs for developing and controlling the transport network to the price for trading one unit of electric energy.

Consequently, the utility of each consumer $c_r,\ r = 1, \dots, k$ can be expressed by

$$u_{c_r}^t(q) = \|q\|_1 \cdot \left(v_{c_r}^t - p\right). \tag{4.16}$$

The utility function of every seller $s_h, h = 1, \dots, n$ is given by

$$u_{s_h}^t(q) = \|q\|_1 \cdot \left(p - v_{s_h}^p\right). \tag{4.17}$$

In addition, the expenses of the investors and the network operators are determined by a one-sided auction design. Therefore, the gains of trades are similar to the difference between the individual value of the winner and the second lowest bid.

4.3. Concept of the Integrated Electricity Market Design (IEMD)

Taking into account the relevant funds that are needed to keep the transmission network operational, it is also necessary to pay attention to the process of defining responsibilities and compensation for investments in network capacities. Consequently, the concept of this mechanism is to guarantee a payback for the investors and service providers that equals exactly their initial expense. Therefore, the proposed mechanism consists of two steps. In addition, a complete supply of consumers is seen as important for a reliable energy supply. Double auctions that exclude sellers from the auction in order to compute the trading price (e.g. the double auction from Ausubel (ref. Ausubel, 2004) or the ICDA from chapter 2) are not practicable for the allocation in the electricity market design.

First, the necessary investments in increasing or reducing the transport capacities for the next period of time are defined. On the one hand, the necessity of changes in network capacity can be determined by analyzing the long-term demand and supply sent in by the agents. On the other hand, strategic consideration could require the creation of additional transport capacities. For instance, changes in energy production towards renewable energy lead to immense transformations in the structure of the network. For now, it is assumed that the need of creating additional transport capacities is known prior to the start of the auction.

Second, the operation services are allocated similarly to the process of the investments. After building network routes, it is necessary to keep these routes in working order. For each stage, one operation service company is defined that is responsible to keep the stage in working order. As compensation the responsible company gets a certain income that equals the second lowest bid. The trade of electric energy itself is addressed by a double auction. In order to include the costs for transportation into the allocation phase, methods of the minimum-cost flow patterns from Busacker and Gowen (ref. Busacker & Gowen, 1960) are used. In each step of the allocation the additional energy trade is defined by searching for the nearest producer with free capacity. This is done until the demand of each buyer is satisfied.

In order to generate an allocation process that considers production cost and network costs similarly it is necessary to start with the customers as sources of the flow problem. Otherwise, production cost would be dominating and the auction would not achieve a competitive situation for the transmission capacities.

Integrated Electricity Market Design (part 1):

1. Definition of the investments in the network capacities

   The auctioneer decides which investments in expansion or reduction of transport capacities have to be carried out. For the calculation of the equivalent of the investment, the auctioneer sets up a one-sided auction similar to the well known VCGm.

   For this reason, the investments are grouped, i.e. $I^t = \{I_1^t, I_2^t, \dots\}$ defines the investment bundles of time period t. For each investment bundle a separate one-sided auction is used. As a result, the auctioneer defines the price for each bundle $p(\tilde{I}), \tilde{I} \in I^t$ corresponding to the second lowest bid[46].

2. Definition of the costs of the operating services

   For each segment of the network the auctioneer sets up a one-sided auction in order to define the responsible operators for the next period of time, and the corresponding operation fees.

   For this reason, the operation services are grouped, i.e. $U^t = \{U_1^t, U_2^t, \dots\}$ defines the operating service bundles of time period t. For each operating service bundle a separate one-sided auction is used. As a result the auctioneer defines the price for each bundle $p(\widetilde{U}), \widetilde{U} \in U^t$ corresponding to the second lowest bid.

   Consequently, the financier of $\widetilde{U} \in U^t$ is the agent $\bar{o} \in O$ with the lowest offer.

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[46] In case there is no unique minimum bid the auctioneer chooses the financier randomly.

Remark: As mentioned above, the auction of the investment bundles and the operation service packages is constructed by using several one-sided auctions. As these auctions are based on the well known VCGm the Integrated Electricity Market Design (part 1) is individually rational, allocative efficient and incentive compatible. ■

Integrated Electricity Market Design (part 2):

3. Allocation of electricity:
    a. All buyers and sellers are asked to send in their demand and their individual value referring to that demand. Without loss of generality, it can be assumed that the customers are sorted according to their private values, i.e.
    $$v_{c_1}^t \geq v_{c_2}^t \geq \cdots \geq v_{c_k}^t.$$
    b. Compute the matrix $\Xi = \begin{pmatrix} \xi_{1,1} & \cdots & \xi_{k,1} \\ \vdots & \ddots & \vdots \\ \xi_{k,1} & \cdots & \xi_{k,n} \end{pmatrix}$ for which $\xi_{h,r}$ reflects the shortest distance from each buyer c_h to every seller s_r including the marginal price $v_{s_r}^t$.

    Initialize the matrix $\Omega = \begin{pmatrix} \omega_{1,1} & \cdots & \omega_{k,1} \\ \vdots & \ddots & \vdots \\ \omega_{k,1} & \cdots & \omega_{k,n} \end{pmatrix} = W^t$ for which $\omega_{h,r}$ reflects the current maximum network flow from each buyer c_h to every seller s_r.

    The quantity matrix is initialized, i.e. $Q^t = \begin{pmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0 \end{pmatrix}$.

```
c. For $h = 1$ to $k$
       While $\sum_{r=1}^{n} q_{c_h,s_r,}^{t} < d_{c_h}^{t}$ and $\min_{i=1,\dots,n} \xi_{h,i} < \infty$
           $r = \operatorname*{argmin}_{i=1,\dots,n} \xi_{h,i}$.
       $q_{c_h,s_r}^{t} = q_{c_h,s_r}^{t} + min\left(d_{c_h}^{t} - \sum_{i=1}^{k} q_{c_h,s_i}^{t}, g_{s_r}^{t} - \sum_{j=1}^{n} q_{c_j,s_r}^{t}, \omega_{h,r}\right)$.
           $\xi_{h,r} = \infty$.
           If $g_{s_r}^{t} = \sum_{j=1}^{k} q_{c_j,s_r}^{t}$ the
               For $i = 1$ to $m$
                   $\xi_{i,r} = \infty$.
               Next
           End if
           Ω is updated according to the added power flow.
       End While
   Next
```

d. The price is defined by

$p^* = v_{s_r}^{t} + z(I^t, U^t, Q^t) = v_{s_r} + \frac{\sum_i p(I_i^t) + \sum_i p(U_i^t)}{\sum_r \sum_h q_{c_h,s_r}^{t}}$.[47]

e. If $v_{c_k}^{t} < v_{s_r}^{t} + z(I^t, U^t, Q^t)$ remove c_k from the auction $(k = k - 1)$ and return to a.

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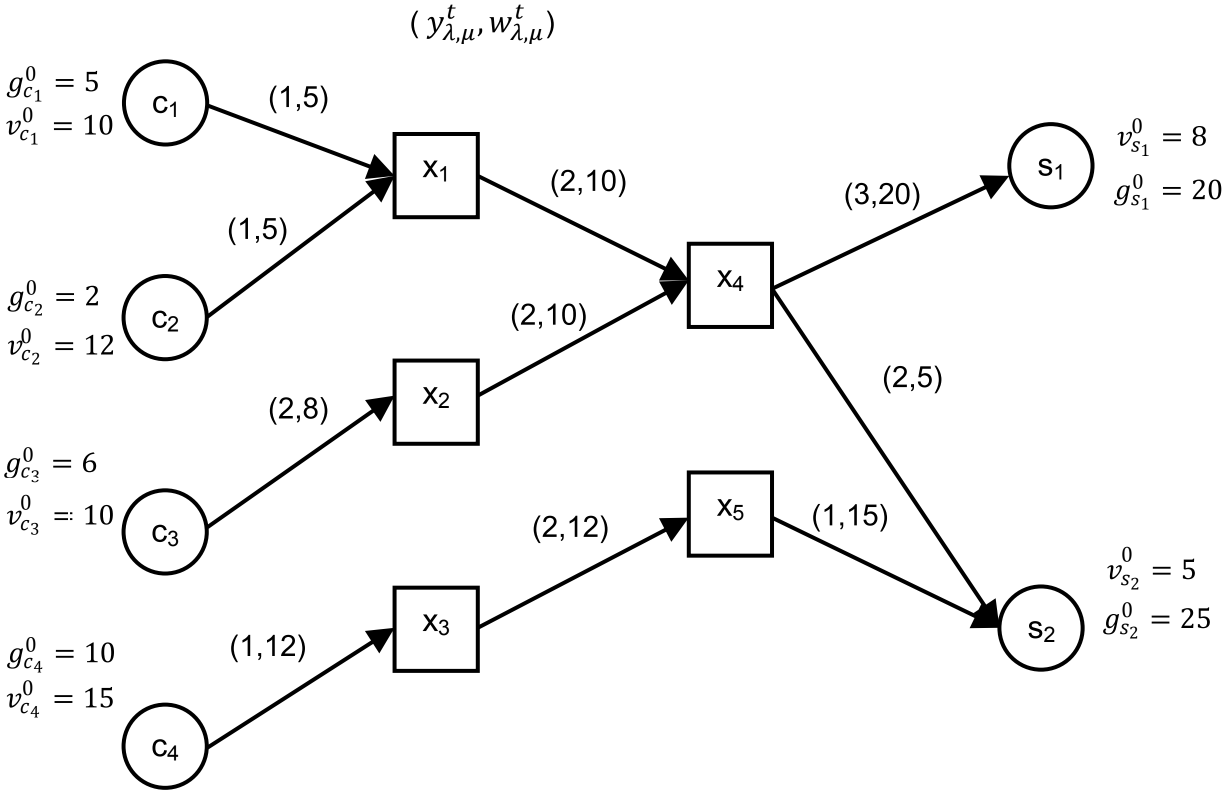
[47] The price function of step d. could be replaced by any function $z(I^t, O^t, Q^t)$ according to the preferences of the auctioneer.

Example 3:

In the following, an example of the Integrated Electricity Market Design (IEMD) is presented that consists of four consumers and two producers of electric energy.

The following picture illustrates the structure of the energy network.



The network costs are described by the matrix

$$Y^0 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3 & 2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

and the corresponding network capacities are described by

$$W^0 = \begin{pmatrix} 5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 8 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 12 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 12 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20 & 5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 15 \end{pmatrix}.$$

It is assumed that the cost for the investments and that for the operation services have already been fixed: $\sum_i p(I_i^0) = 12$ and $\sum_i p(U_i^0) = 7$.

The buyers are sorted according to their individual values,

i.e. $v_{c_4}^0 > v_{c_2}^0 > v_{c_1}^0 \geq v_{c_3}^0$.

Results of the IEMD:

c_4: The shortest distance to a producer is c_4 to s_2 with a maximum capacity of 10 and a total cost of 9.

Consequently, buyer c_4 purchases 10 units from seller s_2 using the route

$c_4 \rightarrow x_3 \rightarrow x_5 \rightarrow s_2$.

c_2: The shortest distance to a producer is c_2 to s_2 with a maximum capacity of 10 and a total cost of 10.

Consequently, buyer c_2 purchases 2 units from seller s_2 using the route

$c_2 \rightarrow x_1 \rightarrow x_4 \rightarrow s_2$.

c_1: The shortest distance to a producer is c_1 to s_2 with a maximum capacity of 3 (due to the limits of $x_4 \rightarrow s_2$) and a total cost of 10.

Consequently, buyer c_1 purchases 3 units from seller s_2 using the route

$c_1 \rightarrow x_1 \rightarrow x_4 \rightarrow s_2$.

As buyer c_1 demands 5 units, the mechanism skips to the next seller.

The shortest distance to a producer is c_1 is to s_1 with a maximum capacity of 2 and a total cost of 14.

Consequently, buyer c_1 purchases 2 units from seller s_2 using the route

$c_1 \rightarrow x_1 \rightarrow x_4 \rightarrow s_1$.

c_3: The shortest distance to a producer is c_3 to s_2 with a maximum capacity of 0 and a total cost of 14.

Consequently, buyer c_3 purchases 0 units from seller s_2 using the route

As buyer c_3 demands 6 units, the mechanism skips to the next seller.

The shortest distance to a producer is c_3 to s_1 with a maximum capacity of 8 and a total cost of 15.

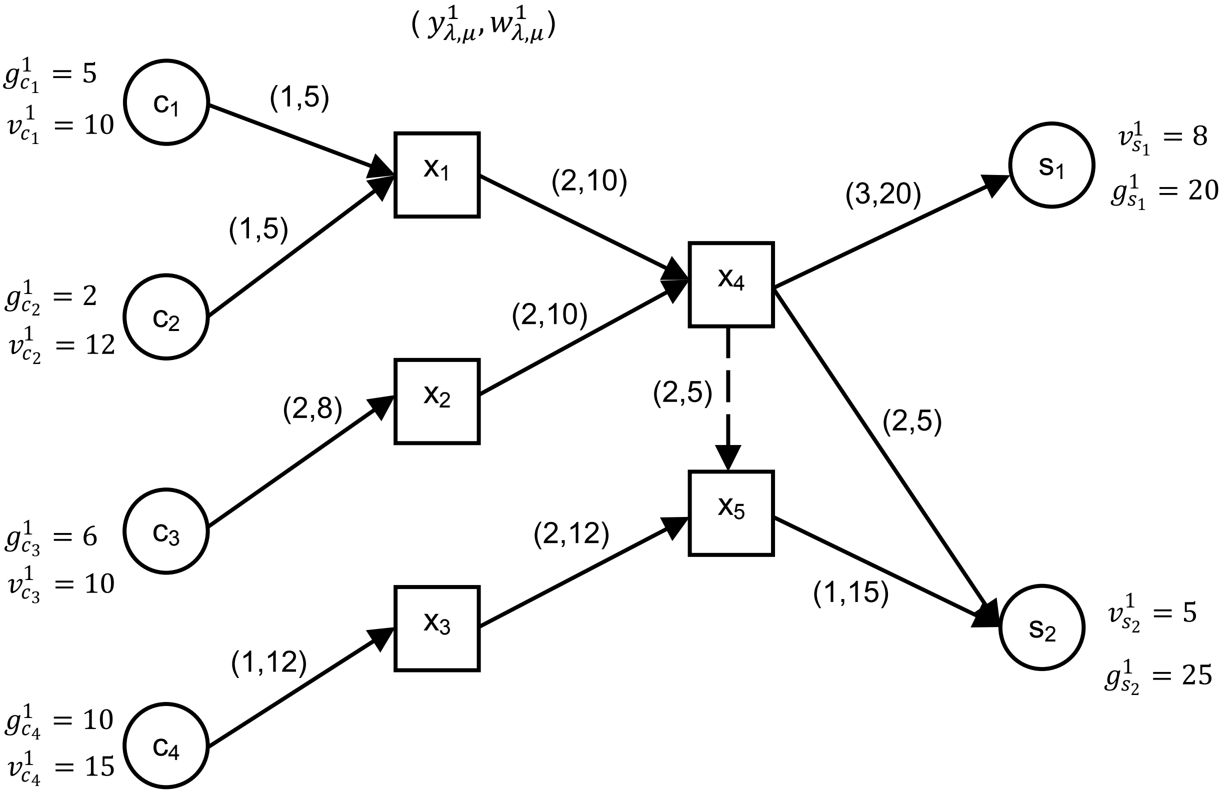
Consequently, buyer c_3 purchases 8 units from seller s_1 using the route

$c_1 \rightarrow x_1 \rightarrow x_4 \rightarrow s_1$.

The trading price is set to $p^* = v_{s_1}^0 + \frac{\sum_i p(I_i^0) + \sum_i p(U_i^0)}{\sum_r \sum_h q_{s_r,c_h}^0} = 8 + \frac{19}{38} = 8.5$.

Besides the allocation the auctioneer gets as a result of the IEMD the current limits of the transmission network. When examining the next producer from c_1 it turns out, that the network capacity $x_4 \rightarrow s_2$ is nearly used at this period of time. As a consequence, c_1 has to pay a higher price for the last 5 units to be traded.

The following picture illustrates the structure of the energy network with an adapted transmission network (ref. y_{x_4,x_5}^1 and w_{x_4,x_5}^1).



In order to use the remaining production capacities of c_1 sufficiently the auctioneer could either invest in additional capacity of route $x_4 \rightarrow s_2$ or build the route $x_4 \rightarrow x_5$. Supposing that valid data about future demand and offer is available the problem of finding the favorable investment or non-investing is well defined.

Actually, the additional link between x_4 and x_5 leads to an increased gain from trade of 15 cost units. ■

As mentioned above it is essential to separate the totality of power trades into several markets that are distinguished in the durance of their contracts. Considering the inefficiencies of power trades that occur from short-term changes the separation into intra-day, day-ahead and long-term auctions is important. Consequently, it is convenient to implement several instances of the IEMD for intra-day, day-ahead and long-term power markets.

Another aspect that supports the idea of implementing several IEMD with varying contract durations is the fact, that additional information is necessary to determine needs for improving the transmission network. Based on long-term information and the network deficit analyses of the current trades the auctioneer is able to identify the next steps of network modifications. In addition, non-economic consideration, such as sustainability and urban development, could be regarded to define the investment bundles $I^t = \{I_1^t, I_2^t, \ldots\}$ at the beginning of the auction.

The economic demand for further transmission capacities could be based on the potential costs for investing in comparison to the expected surplus of future trades. Several instances of the IEMD could compute allocation scenarios based on the data about future demand, offer and marginal prices that each agent reveals to the auctioneer.

4.4. Characteristics of the Integrated Electricity Market Design (IEMD)

Finally, this section analyzes which properties the IEMD satisfies and which assumptions have to be made. Furthermore, the consequences of the assumptions for an implementation in real life are discussed.

As mentioned above, the main properties of mechanism design are individual rationality, budget balance, incentive compatibility and allocative efficiency. According to the studies of Myerson and Satterthwaite (ref. Myerson & Satterthwaite, 1983), it is impossible to create a double auction that simultaneously satisfies these four properties. As a consequence, at least one of them has to be relaxed in order to satisfy the others. The IEMD ensures the properties budget balance and individual rationality, but allocative efficiency and incentive compatibility are not completely satisfied.

Proposition 4.1: The IEMD is budget balanced and individually rational.

Proof: First, budget balance is achieved as the payments of the consumers equal exactly the sum received by the producers. In addition, the investments and the operation service fees of time period t are completely balanced by the surcharge $z(I^t, U^t, Q^t)$.

Second, each agent has got a non-negative outcome due to the structure of the auction. This property is ensured as only trades are considered for which the condition $v_s^t + z(I^t, U^t, Q^t) \leq v_c^t$ is satisfied.

Consequently, the IEMD is budget balanced and individually rational. □

Regarding step 3.d. of the IEMD, the trading price is defined by using the individual value of one seller. In fact, the trading price is set according to the value of the producer that has been considered during the last trade of the auction. As a consequence, there exists an incentive for at least this agent to misrepresent her own value in order to increase the price. Due to this fact, the mechanism is not incentive compatible, although the chance of finding a bidding strategy that generates a higher outcome compared to acting honestly vanishes if the number of agents increases (ref. Satterthwaite & Williams, 1989). In addition, the maximum benefit of cheating is limited from above by the next potential supplier – the first one not considered during the auction.

Proposition 4.2: If network capacities are sufficient and the energy reserve satisfies the condition $R_e > 2 \cdot \max_{s \in S} v_s^t$ with $v_s^t < \infty$, the IEMD is short-term efficient, i.e. the mechanism maximizes the gain from trade.

Proof: Supposed that there exists an allocation $\bar{q}$ that creates a higher total gain from trade than the proposed solution q^*, the sum of the buyers' gains from trade or the sum of the sellers' gains from trade have to exceed that of the proposed mechanism,

i.e.

$$\sum_{r=1}^{k} u_{c_r}^t(q^*) > \sum_{r=1}^{k} u_{c_r}^t(\bar{q})$$

or

$$\sum_{h=1}^{n} u_{s_h}^t(q^*) > \sum_{h=1}^{n} u_{s_h}^t(\bar{q}).$$

First, the sellers are sorted in descending order according to their bids. Second, the energy trade is allocated by assigning the minimum cost flow, including the cost for production. For this reason, if network capacity is not a limiting factor the allocation found by the proposed mechanism minimizes the production costs. Furthermore, the assumption $R_e > 2 \cdot \max_{s \in S} v_s^t$ with $v_s^t < \infty$ guarantees that there is a competition for the last power trade. As a consequence, the gain from misrepresenting the true values is limited and do not change the total gains from trade, i.e. the mechanism is allocative efficient. □

Remark: If the information about future values and future demand and supply are reliable, then the IEMD facilitates an efficient development of the transport network. Considering the assumption of proposition 4.2 about sufficient network capacities, the auction of IEMD can give an indication where to expand or reduce the capacities of the network and the electricity production. If a trade cannot be carried out because of missing transport capacities, the principal gets an indication where to enlarge the network. As a result, it is possible to achieve long-term efficiency if the signals about future demand and supply are reliable. Consequently, the main task for a central regulation is to ensure the quality of the agents' prognoses. ■

Proposition 4.3: Considering service providers and investors, the IEMD is incentive compatible without further assumptions. If it can be assumed that the network capacities are sufficient, the buyers have no inventive to misrepresent their true values. Considering the producers, the gain from misrepresenting the true values is limited if there exists an upper bound $\bar{v} = \max_{s \in S} v_s^t$ for the producers' values.

Proof: The allocation of single investment bundle or a single operation service bundle is executed in a separate first-price auction before the electricity allocation process. The concept of the IEMD is that each investment of $I^t = \{I_1^t, I_2^t, \dots\}$ and each operation service package of $U^t = \{U_1^t, U_2^t, \dots\}$ is refinanced by the sale of electricity. As a successful auction of the IEMD refinances exactly the sum the investors and operators spent in step 1. and step 2., the IEMD is incentive compatible regarding the service providers and investors.

In addition, the buyers have no incentive to misrepresent their true values as the individual information of the buyers are only used in step 3.a. of the IEMD (to sort the buyers according to their values) and in step 3.c. (to decide whether to execute a certain trade or not). Taking into account that the trading price $p^* = v_{s_r}^t + z(I^t, U^t, Q^t)$ is calculated without using the individual information of the buyers, it is clear that the buyers have no incentive to signal false information in order to influence the trading price. Supposing that the network capacities are sufficient, all buyers receive the demanded amount of electric energy due to assumption (4.15). As a consequence, the IEMD is incentive compatible for the buyers if the network capacities are sufficient.

Considering the last trade, the involved seller $v_{s_r}^t$ has an influence on the trading price $p^* = v_{s_r}^t + z(I^t, U^t, Q^t)$. Furthermore, each producer could gain from signaling false values as the individual values of the producers are considered by the minimum cost flow of step 3 of the IEMD. The gain from signal false values is limited by the individual value of the next producers with free capacity. Consequently, the gain from misrepresenting the true values is limited. □

4.5. Discussion of the properties of the Integrated Electricity Market Design (IEMD)

In short, the main idea of the IEMD is to bring together all relevant participants of an energy supply chain. As a consequence, it is necessary to discuss whether it is essential to distinguish stringently between the different types of participants, or if it is possible that one company could act in different roles of energy supply. For instance, it is necessary to investigate if a producing company could also invest in additional network capacities that are directly linked to their own power plants. For this reason, the most important aspect is to clarify if incentives arise to act dishonestly. In fact, some regulation is necessary to predict the main incentive incompatibilities that arise if energy-producing companies also invest in transmission capacities.

Taking into account that in step 3.b. of the IEMD the costs for transportation and production are used for allocation, it is obvious that producers may have incentives to consciously signal lower investment costs in order to facilitate the building of additional network capacities that connects their plant. This means producers may have an incentive to underrate the costs for connecting their power plants to gain from a more competitive network in future auctions. As a summary, if a producer cannot sell her complete production due to a limitation of network capacities, she may be interested in misrepresenting the true value for an investment in order to sell more electricity in the following auctions. Consequently, the central authority has to avoid these incentive incompatibilities by forbidding producers to invest in network capacities that are closely linked to their own power plants.

In contrast, a close collaboration between an energy producing company and an operation service provider does not induce comparable incentives to act dishonestly. The main difference between an investment in additional network capacities and the operation service of an existing network is that an investment is carried out once, whereas the operation service has to be maintained as long as the network is in order. Due to the fact that operation service packages are announced more often than investments, the incentive incompatibilities that arise from collaboration between a producer and a service provider are comparatively small. Additionally, keeping the transmission network in working order does not increase its capacity. Consequently, service providing has no influence on the allocation process of the IEMD.

Finally, it has to be investigated if adverse effects for the incentive compatibility are expected if buyers also act as investors, producers or service providers. Considering the formulation of the IEMD, the buyers are sorted in a descending order according to their individual values. In addition, the trading price per unit of electric energy is constant in each period of time. Obviously, buyers cannot increase their gains from trade by acting dishonest, if their demand for electricity is completely supplied.

Finally, the relaxations made in section 4.2 concerning the lossless distribution of electric energy and Kirchhoff's second have to be considered. Obviously, the IEMD can be extended to represent the distribution losses by changing the definition of the transmission cost matrix $W_{s,c}(Q^t)$. Additionally, the extra production to balance the losses of the transmission has to be regarded in the allocation phase of step 3.c.

In order to integrated the requirements of Kirchhoff's second law it is essential to adapt the method for computing the maximum flow in step 3.b. Instead of determining a single route from a buyer to a seller it is necessary to pay attention to a consistent flow in parallel routes and circles.

In recent years, the scientific discourse about energy supply demands for an integrated concept to combine a long-term efficient, reliable and sustainable electricity market design that also assists the development of the transmission network. Therefore, the Integrated Electricity Market Design (IEMD) enlarges the existing models by proposing a market-based concept that is budget balanced, individual rational and which facilitates short-term and long-term efficiency. Furthermore, the IEMD provides a concept for a low-risk investment in network capacities that advances the market entrance for new financiers. In addition, the incentives to misrepresent the true values are limited and only existent for the producers of electric energy.

5. Conclusion

In this dissertation auction formats are developed and discussed that focuse on three specific economic environments. Regarding the impossibility results from mechanism design, the main task for the implementation of auction designs is to balance allocative efficiency and incentive compatibility – the main characteristics a mechanism should provide.

Therefore, the dissertation investigates the limits of conceivable relaxations of allocative efficiency and incentive compatibility for complex settings such as double auctions, interdependent-valuation environments and electricity market designs. The overall aim is to carefully weigh up the advantages and disadvantages for either relaxing allocative efficiency or respectively incentive compatibility.

For instance, the direction of the flow optimization of the Integrated Electricity Market Design (IEMD) enables the participation of all potential buyers. Therefore, agents whose private information is needed to compute the trading price and to allocate the electric energy remain in the allocation process of the IEMD. Although this creates incentives to misrepresent the true values it is seen as more important that energy supply must be dependable. Costs for a lack of energy supply due to the definition of the auction design may be significant for a single agent. In contrast, the Incentive Compatible Double Auction (ICDA) accepts that a selection of buyers and sellers are removed from the allocation process in order to prevent incentive incompatibilities. Consequently, the concrete consideration whether to relax allocative efficiency or incentive compatibility depends on the specific application of the auction design.

As a summary, the dissertation concentrates on three complex economic environments and enlarges existing auction concepts. Thereby, a double auction is presented that achieves budget balance, individual rationality and incentive compatibility for private-valuation environments without further assumption concerning the individual values. Furthermore, the proposed double auction is asymptotically allocative efficient for single-unit markets and multi-unit markets with homogeneous goods, if the number of participants grows. For multi-unit market with heterogeneous goods the achievement of asymptotical allocative efficiency depends on the homogeneity of the buyer-seller-structure.

Another important aspect this dissertation addresses is Wilson’s demand for mechanisms that request less individual information for allocation processes. So, the presented dynamic auction for interdependent-valuation environments enlarges the existing concepts as it requires less individual information from the agents as existing static auction formats. Additionally, the Alternating-Price Auction (APA) broadens the scope of application for dynamic auctions as it relaxes the activity rule of Ausubel’s Ascending-Bid Auction.

Finally, the concept for power markets described in chapter 4 offers the type of an “integrated market design” Wilson asked for (ref. Wilson, 2002, p.1304). The Integrated Electricity Market Design (IEMD) facilitates short-term and long-term efficiency while at the same time provides a concept for enabling low-risk capital expenditures in transmission capacities. Thereby, the IEMD introduces a setting that involves several relevant stakeholders as energy-producing companies, investors, service providers and consumers. Obviously, the balancing of the conflicting interests of these stakeholders is the main task for designing adequate electricity markets. As a summary, the IEMD provides a markets concept that facilitates short-term and long-term efficiency properties while at the same time it offers an innovative idea of removing market entry barriers for new investments in transmission network capacities.

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