

# Socially optimal allocation of ATM resources via truthful market-based mechanisms

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**Abstract**—This is a position paper, complementing existing research on design of economic incentives for allocation of ATM resources and services. We show how to design mechanisms that can be used for the allocation of many different types of ATM resources, including tactical flow management slots and airport facility resources. In particular, we discuss the example of arrival management when multiple aircraft request the same landing time.

The mechanisms we present are *socially optimal* (i.e., resources are distributed in the way that best serves the users community as a whole), *truthful* (i.e., each individual user has incentive to play fairly), and, under certain assumptions, *individually rational* (i.e., users lose nothing from entering the market). However, they are not *budget balanced* (i.e., the resource owner gains profit from the users' payments). Earlier, it was shown how to design individually rational, budget balanced and (sometimes) socially optimal mechanisms.

We also discuss other possible desirable properties of resource allocation schemes, outlining directions for future research in the design of markets for ATM services.

## I. INTRODUCTION

Many ATM resources may be put onto an open market (auction), where users would express interest in the resources by submitting bids for them. A bid for a resource is a measure – often monetary – of the willingness of the user to access the resource. Based on the bids, the resource owner will allocate the resources to the users and will charge the users according to the allocation. The price that a user pays for the resource may not necessarily be equal to the user's bid; in particular, the price may be negative, meaning that the user is getting paid for being allocated an unfavored resource.

The exact meaning of the bids may vary from application to application. E.g., in the scheduling domain, the resources may be service time slots (for a more concrete example, think of tactical arrival slots to an airport), and the bid may represent the cost per minute that the user incurs while waiting (say, for an available landing time). For companies leasing space in an airport, the resources may be, e.g., possible locations of check-in desks, shops or cafeterias, and the bid may express a company's valuation of renting a particular spot. Overall, there is a great variety of places in the air traffic industry where the bidding–allocation–pricing procedures can be adopted to provide cost-based access to services and resources.

## A. Properties of mechanisms

The rules that the resource owner follows when allocating the resources and establishing the charges play a crucial role in the process. Over the years, several desirable properties of the allocation-and-pricing mechanisms have been identified:

- **social optimality (SO)**: the allocation should maximize benefit to the society.
- **incentive compatibility (IC)**: no user shall benefit from lying.
- **individual rationality (IR)**: each user should get a non-negative utility.
- **budget balance (BB)**: the resource owner's net profit must be 0.

We elaborate on the definitions of the properties in Section II where we give a formal treatment of mechanisms.

1) *Terminological remarks*: The above properties have appeared in the literature under various names:

- Another name for social optimality is *social welfare maximization*; socially optimal mechanisms are thus also called *social welfare maximizers*. Yet another name for a socially optimal mechanism is *efficient*.
- Another name for incentive compatibility is *truthfulness*; incentive-compatible mechanisms are thus also called *truthful*. Yet another name for a truthful mechanism is *strategyproof*.
- Another name for individual rationality is *participation constraint*.

Note that SO and BB are global properties – they are defined in terms of the users community and the system as a whole, while IC and IR are local properties – they are relevant for each single user's interaction with the mechanism.

## B. Impossibility results

We immediately recall strong impossibility results related to mechanism design:

- Only an incentive-compatible mechanism can achieve social optimality. Indeed, if the users do not report true information, how would the mechanism know what output best serves the users?
- No mechanism can simultaneously have all four—SO, IC, IR and BB—properties [1].

### C. Related work

One of the seminal papers on mechanism design in ATM is that of Rassenti et al. [2], where combinatorial auction for airport slots was introduced. Vossen and Ball [3], [4] studied exchanges of single and multiple slots. Ball et al. [5] gave a general treatment of auctions in ATM.

Recently, the mechanism design area has seen an influx of activity, since application of economic incentives for pricing ATM services and auctioning available resources has become an important part of SESAR's vision of the future air transportation system; the vision has brought up the challenge of establishing the "right" rules according to which the resources will be distributed to end users, and the "right" prices that the users will be charged for access to the resources and services. In particular, in a series of papers [6]–[11] Castelli, Pellegrini, Pesenti and Ranieri presented allocation and pricing mechanisms for ATM applications. The emphasis in most of the papers was on designing *individually rational* and *budget balanced* mechanisms; in many cases, the mechanisms were also *socially optimal*. Unsurprisingly (in view of the impossibility results, Section I-B), the mechanisms in [6]–[11] are not necessarily truthful.

The motivating application in the work of Castelli, Pellegrini, Pesenti and Ranieri was airport and enroute slot allocation (their mechanisms may be applicable to other ATM domains as well). In large part, the work adhered to the concept of User Driven Prioritisation Process (UDPP): it was assumed that some initial resource distribution is given — the aircraft are already assigned some slots. This starting assignment may come e.g., from the First-Planned-First-Served rule, or, on a more strategic level, from grandfather rights. The mechanism is then concerned with how airlines may trade the slots available to them. The trade is performed via a central market, not directly pairwise between the flights.

### D. Our contribution

This paper is also devoted to the design of market-based mechanisms for ATM resource allocation. We complement the work of Castelli, Pellegrini, Pesenti and Ranieri by presenting *truthful* and *socially optimal* mechanisms; moreover, the mechanisms sometimes can be made *individually rational*. Unsurprisingly (in view of the impossibility results, Section I-B), the mechanisms in this paper are not necessarily budget balanced.

Another, more subtle, difference between the mechanisms in this paper and those in earlier work is that we do not assume that any initial allocation of the resources is given to the users. That is, we compute the socially optimal allocation "from scratch", and the users' charges are set so as to enforce truthfulness of the mechanism.

The table below compares the mechanisms in this paper with the ones in the previous work in terms of the important properties possessed by the mechanisms.

	SO	IC	IR	BB
Earlier work	Possibly	No	Yes	Yes
This paper	Yes	Yes	Possibly	No

We emphasize that this is a position paper: the mechanism presented below is not an invention of ours; on the contrary, it is a classical part of the economic theory, and our contribution is merely the introduction of the mechanism to the ATM domain. We note however that even though many parts of the theory of truthful mechanism design have been already developed, a lot of research effort is still needed to adapt the theory to ATM reality.

### E. Application to arrival management

A running example, on which we will illustrate application of the presented mechanisms in the ATM domain throughout the paper, will be arrival management. In the specific case that we consider, multiple aircraft request a landing slot at the same time, and the arrival manager has to sequence these aircraft taking into account the costs incurred by the aircraft during holding. All aircraft will thus receive a landing slot that is equal to the requested time, or later than the requested time.

In particular, we show how to design truthful mechanisms for socially optimal allocation of the landing slots. To our knowledge, such mechanisms have not appeared previously in the literature.

In general, application of the described mechanisms is not limited just to arrival management; the mechanisms can be applied in any setting where multiple users are competing for resources.

### F. Outline of the paper

The mechanisms and their properties are formally defined in Section II. Section III outlines Vickrey–Clarke–Groves mechanism – the truthful mechanism maximizing social welfare; Section III-A gives Clarke pivot rule that makes the mechanism individually rational. Section IV discusses general market features and outlines directions for future research.

## II. FORMAL DEFINITIONS

Consider the following generic setting, frequently encountered in industry: A set of users compete for resources that belong to a *resource owner*. The owner allocates the resources to the users based on the information that the users submit to the owner, and charges the users according to the allocation. Some fundamental questions that arise in such situations are:

- What information should the owner solicit from the users?
- How to ensure that the users submit true information?
- How to allocate the resources?
- What prices should each user pay for the obtained resource?

In this section we formalize the above questions, and give answers to some of them.

### A. Notation

Let  $n$  be the number of users; a generic user is denoted by  $i$ . Let  $A$  be the set of all possible resource allocations. That is,  $A$  is the set of all possible ways in which the resources may be distributed to the users.

In the arrival management example, the users are aircraft, and  $A$  is the set of all possible assignments of slots to users. For an assignment  $a \in A$ , let  $a(i)$  denote the slot assigned (allocated) to the user  $i$ .

### B. Valuations

Each user  $i$  has a *valuation*,  $v_i(a)$ , for every allocation  $a \in A$ . The valuation  $v_i(a)$  is a number that indicates how much the user  $i$  is satisfied with the allocation  $a$ . That is,  $v_i$  is a function from  $A$  to the set  $\mathbb{R}$  of real numbers,  $v_i : A \mapsto \mathbb{R}$  (the valuation may be negative if the user is dissatisfied with the allocation). Most often the valuation  $v_i(a)$  depends only on the resources that the user  $i$  herself receives in the allocation  $a$  (a rational user  $i$  does not care about how the remaining resources are distributed to the other users); however, in a more general case  $v_i(a)$  may also depend on the resources obtained by the other users. The valuation is *monetary*, meaning that it is measured in Euros.

In the arrival management example,  $v_i(a)$  is the valuation of the user  $i$  of the landing slot  $a(i)$  assigned to her. In the simplistic case of *linear valuations*, each user  $i$  has a monetary value  $C_i$  for landing at the airport; also, the user  $i$  loses  $w_i \geq 0$  Euros per every slot that she has to wait. Then the valuation of  $i$  for the slot assignment  $a$  is given by

$$v_i(a) = C_i - w_i \cdot a(i) \quad (1)$$

That is, the valuation is a (decreasing) linear function of  $a(i)$ . Of course, having linear valuation functions (1) is a very special, simple case, hardly relevant in practice. We use it only for illustrative purposes, to demonstrate specific properties of the presented mechanisms.

In general, dependence of the user's valuation on the assigned landing slot is not linear. First of all, different aircraft arrive to the terminal area at different times and have different preferred landing times (e.g., slot #1 is not necessarily the highest-valued for all users). Second, even for a single aircraft the valuation for slots is not linear. E.g. for one aircraft a delay of 10 min would be perfectly acceptable, due to existing time buffers, while a longer delay would affect consecutive flights with the same aircraft, passenger connections and so on. Furthermore, any delay longer than 30 min may have serious consequences for an aircraft due to fuel shortage. In addition, an aircraft may incur costs if it lands before the preferred arrival time. There are many other reasons to assume that the valuation functions in the arrival management application are non-linear.

The mechanisms presented in this paper are applicable to the case of arbitrary, general valuation functions. That is, the user is free to specify an arbitrary (no matter how complicated) table giving her valuations for each of the slots. The mechanisms will work with such tables just fine. In what follows we explain how to use the mechanisms in this general, non-linear case; i.e., our exposition is not limited to the case of linear valuations (1).

1) *Specification of a valuation*: In general, specifying a valuation function  $v_i$  may entail a lot of information – one number,  $v_i(a)$ , must be specified for each allocation  $a$  from the set  $A$  of all possible allocations, and  $A$  can be a huge set. However, in many cases the valuation  $v_i$  is given by a simple formula, so specifying the valuation amounts to transmitting only the parameters of the function. E.g., if valuations are given by (1), just two numbers,  $C_i$  and  $w_i$ , per user must be sent in order to fully specify the function  $v_i$ .

### C. Social welfare

Not all allocations are equal, and different users may prefer different allocations of the resources. However, some allocations are good from the point of view of the community as a whole, because their overall valuation is high. Specifically, the *social welfare* of an allocation  $a \in A$  is defined as  $\sum_i v_i(a)$ , i.e., as the total valuation of  $a$  by all the users. An allocation  $a^* \in A$  is called *socially optimal* if it maximizes the social welfare:  $\sum_i v_i(a^*) = \max_{a \in A} \sum_i v_i(a)$ .

In our running example, the socially optimal allocation is given by the maximum-valuation assignment of slots to the users. Such an assignment can be computed efficiently for arbitrary valuations, since it is exactly equivalent to the classical algorithmic problem of finding maximum-weight matching in a bipartite graph [12, p. 68]. The maximum-valuation assignment can be computed efficiently even in the case when the capacity of each slot is an arbitrary number, possibly larger than 1.

In the special case of linear valuations (1), the socially optimal assignment is a greedy one: the user with highest  $w_i$  is assigned the first slot, the next-to-highest – the second slot, and so on. Such an assignment indeed maximizes the social welfare since it minimizes the total weighted delay of the users (the sum of users delays weighted by the  $w_i$ 's).

### D. Social choice

To decide on the allocation of the resources, the resource owner asks the users to submit their valuation functions. Having received the set  $v = (v_1, v_2, \dots, v_n)$  of valuation functions from all  $n$  users, the owner invokes a *social choice* function  $f$  to choose an allocation  $a \in A$ . That is, formally, a social choice function is a function  $f : V \mapsto A$  from the set  $V$  of all possible valuations to the set  $A$  of all possible resource allocations: given the valuations  $v \in V$ , the social choice function outputs an allocation  $f(v) \in A$ .

1) *Social optimality (SO)*: In general, a social choice function  $f$  may be completely arbitrary. However, some functions are clearly better than others. For instance, a social choice function that allocates the resources in a random way is, perhaps, not a very good function.

One particularly natural social choice function is one that outputs a socially optimal allocation:

**Definition 1.** A social choice function  $f$  is called *socially optimal* if  $\sum_i v_i(f(v)) = \max_{a \in A} \sum_i v_i(a)$ .

In particular, as discussed in the end of Section II-C, in the slot allocation application with linear valuations (1), a

socially optimal function must allocate the slots in the order of decreasing  $w_i$ . Unfortunately, this encourages users to lie, as reporting high values of  $w_i$  implies getting early slots. To remedy this and to enforce truthful reporting of the valuations, the users must be charged for the slot allocations. This is what we discuss next – addition of payments to the social choice functions.

### E. Mechanisms with money

A *mechanism* is a pair  $(f, p)$  where  $f$  is a social choice function and  $p : V \mapsto \mathbb{R}^n$  is the *payment*. Given the set  $v = (v_1, v_2, \dots, v_n)$  of valuation functions from all the users, the mechanism outputs two things: (i) an allocation  $f(v)$ , and (ii) the prices  $p(v) = (p_1(v), p_2(v), \dots, p_n(v))$  that the users have to pay. Here  $p_i(v)$  is the price that the user  $i$  must pay.

**Definition 2.** *Mechanism*  $(f, p)$  is called socially optimal if  $f$  is socially optimal.

E.g., one possible mechanism for arrival management may be as follows:  $f(v)$  assigns slots in the order of decreasing  $w_i$  (i.e.,  $f$  is SO); as for the payments, the user who is assigned the first slot has to pay 1 million Euros, while the others pay nothing. This is not a particularly good mechanism since the users will be afraid of reporting the true values  $w_i$ , scared by the possibility of being assigned to the first slot.

The whole field of truthful mechanism design is concerned with establishing the "right" payments, enforcing users to report their true valuations.

1) *Quasilinear utilities*: With payments in the picture, user's happiness about an outcome  $(f(v), p(v))$  of the mechanism does not depend solely on the resource allocation  $f(v)$ , but also on the price  $p_i(v)$  that the user has to pay. The prevailing model is that the *utility* of user  $i$  is given by  $u_i(v) = v_i(f(v)) - p_i(v)$ . That is, the utility is the user's valuation of the allocation minus the payment. The users are interested in maximizing their utility.

2) *Incentive compatibility (IC)*: The main objective of truthful mechanism design is to find mechanisms in which each user's utility is maximized by truthfully reporting her valuation. This is formally captured in the following definition:

**Definition 3.** A *mechanism*  $(f, p)$  is called incentive-compatible, or truthful if for every user  $i$  and for any reported valuation functions  $v' = (v'_1, v'_2, \dots, v'_n)$  it holds that

$$v_i(f(v')) - p_i(v') \leq v_i(f(v^*)) - p_i(v^*)$$

where  $v^* = (v'_1, v'_2, \dots, v'_{i-1}, v_i, v'_{i+1}, \dots, v'_n)$  are the valuation functions when the user  $i$  truthfully reports her function  $v_i$ .

That is, if  $i$  reports the true valuation function  $v_i$ , her utility is maximized.

3) *Individual rationality (IR)*: A user getting negative utility would be unhappy with a mechanism. It thus makes sense to require that each user always gets a non-negative utility, no matter what the valuations are. Mechanisms that satisfy this property are called *individually rational*. Formally,

**Definition 4.** A *mechanism* is individually rational if for any valuations  $v = (v_1, v_2, \dots, v_n)$ , it holds for any  $i$  that

$$v_i(f(v)) - p_i(v) \geq 0$$

4) *Budget balance (BB)*: In some cases it is desirable that the resource owner neither makes money from the mechanism nor subsidizes the users. (E.g., Castelli, Pellegrini, Pesenti and Ranieri [6]–[10] required their mechanisms to be such.) That is, the net profit of the mechanism is required to be 0. Formally,

**Definition 5.** A *mechanism* is budget balanced if for any valuations  $v$ ,  $\sum_i p_i(v) = 0$ .

It is trivial to make any mechanism budget balanced: just compute  $\sum_i p_i(v)$ , and distribute it among the users. E.g., each user can be charged an additional price of  $\sum_i p_i(v)/n$  for an even distribution of the imbalance among the users. However, making a mechanism BB in this way, may destroy IR of the mechanism.

Similarly, it is trivial to make any mechanism individually rational: just have the mechanism pay a lot of money to each user. However, making a mechanism IR in this way, may destroy the BB property of the mechanism.

Making a mechanism simultaneously BB and IR is non-trivial – and this is what has been the essence of the research by Castelli, Pellegrini, Pesenti and Ranieri [6]–[10].

## III. THE VCG MECHANISM

A *Vickrey–Clarke–Groves (VCG) mechanism* [13]–[15] is a socially optimal mechanism, in which the payment of every user consists of two parts:

- 1) The user pays a fixed charge that does not depend on her valuation.
- 2) The user is paid the total valuation of the other users.

That is, the first part is what the user pays to the mechanism; the second part is what the user gets from the mechanism. Thus, the overall payment of the user is the first part minus the second part. Formally,

**Definition 6.** A *mechanism*  $(f, p)$  is a VCG mechanism if

- $f$  is socially optimal, i.e.,  $\sum_i v_i(f(v)) = \max_{a \in A} \sum_i v_i(a)$ .
- The payment of the user  $i$  is

$$p_i(v) = h_i(v) - \sum_{j \neq i} v_j(f(v)) \quad (2)$$

where  $h_i$  is some function that does not depend on  $v_i$ .

One obvious nice property of a VCG mechanism is that it outputs a socially optimal allocation. The real beauty of the mechanism is that it sets the payments just so as to enforce truthful behavior of the users:

**Theorem 7.** ([13]–[15]) A VCG mechanism is truthful.

### A. Clarke Pivot Rule

Let us turn attention to the "mysterious" term  $h_i$  in the payment (2) of the user in a VCG mechanism. The term has no influence on the behavior of the user since the term does not depend on the user's valuation. That is, no matter what function  $h_i$  is used, the mechanism will remain truthful. This gives the mechanism designer full flexibility in choosing  $h_i$ .

One simple choice is to set  $h_i = 0$ . This does not make much sense since then the mechanism would pay a lot of money to the users (the payment  $p_i(v)$  in (2) will be negative). A particularly good choice for  $h_i$  is provided by the so called *Clarke pivot rule* [14]:

$$h_i = \max_{a \in A} \sum_{j \neq i} v_j(a) \quad (3)$$

That is,  $h_i$  is the maximum social welfare that the society can achieve *without*  $i$ .

Combining (3) with (2) we obtain the following formula for the payment of user  $i$  under Clarke pivot:

$$p_i(v) = \max_{a \in A} \sum_{j \neq i} v_j(a) - \sum_{j \neq i} v_j(f(v)) \quad (4)$$

The first term is the maximum social welfare that the other users can achieve *without*  $i$ ; the second term is the social welfare that the other users achieve when  $i$ 's valuation is also taken into account by the socially optimal function  $f$ . The payment of  $i$  is the difference between the two terms, i.e., the "harm" that the society suffers because  $i$  has joined the society.

Clarke pivot rule has the following nice properties:

- **Individual rationality:** If all valuations are non-negative, then Clarke payments make the mechanism individually rational [14].
- **Computability:** If one has an algorithm for computing socially optimal allocation  $f(v)$ , then one also has an algorithm for computing the Clarke payments  $p_i(v)$  in (4). Indeed, the second term in the Clarke price (4) is just the sum of the valuations for the socially optimal allocation. And first term is the same – the sum of the valuations for the socially optimal allocation, but in the society without  $i$ .

### B. Application to arrival management

We now show how to apply the VCG mechanism with the Clarke pivot rule to obtain a truthful, socially optimal mechanism for landing slot allocation. As described in Section II-C, after the valuations  $v$  of the users are reported to the mechanism, the socially optimal allocation  $f(v)$  is found by computing the maximum-valuation assignment of users to slots. To compute the payments, for every user  $i$ , the following steps are repeated:

- Calculate  $s_i = \sum_{j \neq i} v_j(f(v))$ , i.e., the total social welfare of the other users under the allocation  $f(v)$ . To speed up computations, one may pre-compute  $S = \sum_i v_i(f(v))$  (i.e., the total social welfare under the allocation  $f(v)$ ), and for each  $i$ , obtain  $s_i = S - v_i(f(v))$ .

- Remove  $i$  from the set of users.
- Compute the socially optimal allocation for the community without  $i$  (use the same algorithm that was used to compute  $f(v)$ , just with the reduced set of users).
- Calculate  $h_i$  (3), i.e., the total social welfare under the allocation computed in the previous step.
- Charge user  $i$  the price  $h_i - s_i$ , in accordance with Clarke pivot payment formula (4).

1) *An explicit formula for linear valuation:* It is instructive to see how the above scheme works for the special case of linear valuations (1). As mentioned in Section II-C, in this case the social optimum is given by assigning the slots in the order of decreasing  $w_i$ . Assume that the users are ordered so that  $w_1 \geq w_2 \geq \dots \geq w_n$ ; then user  $i$  gets the slot  $i$ . The total social welfare of all users except for  $i$  is then

$$s_i = \sum_{j \neq i} (C_j - w_j \cdot j)$$

To compute the price that user  $i$  has to pay, it is convenient to split the above sum into two parts – users before  $i$  and users after  $i$ :

$$s_i = \sum_{j < i} (C_j - w_j \cdot j) + \sum_{j > i} (C_j - w_j \cdot j)$$

When  $i$  is removed from the society, the socially optimal allocation is still given by assigning slots in the order of decreasing  $w_j$ . Every user  $j < i$  gets the same slot  $j$  that she had when  $i$  was present. Every user  $j > i$  improves her allocation – she now gets the slot  $j - 1$ . The social welfare of the society without  $i$  is thus

$$h_i = \sum_{j < i} (C_j - w_j \cdot j) + \sum_{j > i} (C_j - w_j \cdot (j - 1))$$

The price that the user  $i$  has to pay is

$$p_i = h_i - s_i = \sum_{j > i} w_j$$

This makes perfect sense: Existence of the user  $i$  harms only the users  $j > i$  (the users  $j < i$  get the same slot irrespectively of whether  $i$  is in the society or not). Because of  $i$ 's existence, each user  $j > i$  has to wait for an additional slot, incurring the cost  $w_j$ . The price  $p_i$  that the user  $i$  has to pay is thus exactly equal to the total additional cost that the society incurs because of the user.

### C. Mechanism's general applicability

We remind that throughout the paper we used arrival management merely to demonstrate usage of the mechanisms in an ATM application. In general, application of VCG mechanisms (and Clarke pivot rule) is not limited to arrival management only; the mechanism can be applied in absolutely any domain (both inside and outside ATM) where a socially optimal, truthful mechanism is called for.

#### IV. CONCLUSION AND DISCUSSION

We presented the Vickrey–Clarke–Groves (VCG) mechanism for competitive resource allocation – a truthful mechanism maximizing social welfare. Under Clarke pivot rule, the mechanism becomes individually rational (assuming the valuations are non-negative). Prior work in mechanism design for ATM focused on mechanisms with other important properties – individual rationality and budget balance [6]–[11]; these earlier mechanisms were often also socially optimal.

##### A. Legislative responsibility

While market-based mechanisms can be thrown (in principle) onto almost all ATM business processes, in practice they should be established only in a few specific cases. In particular, in theory, VCG mechanisms are applicable in any (absolutely any) setting where there is competition for resources. In reality, the responsible authority (of any level – EUROCONTROL, an ANSP, an airport, etc.) will decide on case-by-case basis whether the auction should be established in every concrete application or not, taking into account application-specific rules and regulations, the potential benefits of establishing the market, customer (dis)satisfaction, and even such unquantifiable things as common sense, political situation, and traditions which may be sensitive issues in certain circumstances.

As one example related to arrival management, consider declaration of emergency landing due to fuel shortage. Should airlines be charged for taking priority landing slot due to fuel shortage? A quick answer is No. On the other hand, if underfueling is part of the airline’s business strategy, the airline must be prepared to pay higher landing fees should the fuel shortage emergency arise.

##### B. Future research

The basics of truthful socially optimal mechanisms have been developed many years ago. Still, a lot of work remains to be done to bring the mechanism design theory closer to ATM practice:

- The modeling part remains to be done – how to quantify (i.e., assign monetary values to) the valuations of users (airlines, passengers) for various resource allocation outcomes? EUROCONTROL delay reference costs, passenger Value of Time (e.g., as being researched in the WP-E project POEM) and EU social mobility policy are some topics relevant to the question (as kindly pointed out by a reviewer).
- The theoretical solutions show how to derive the prices from the optimal allocation of the resources; in practice, various computational issues will arise because in many applications computing the optimal resource allocation is a computationally challenging task.
- The ATM domain is dynamic and stochastic in nature due to changing and unpredictable weather, delays, etc.; the mechanisms have to be adapted accordingly. E.g. the usage under a dynamic setting requires short computation times and, probably, automatic bidding.

- The theory is valid only for mechanisms that optimize *overall* social welfare (e.g., minimize the total delay incurred by all aircraft competing for the landing slots). In practice many other objectives may be of interest (e.g., minimizing the maximum incurred delay). To date, there exists no general theory for handling such cases.
- A user may consider her valuation function to be her private information, which she would not want to submit to the resource owner. It is important to investigate how to ensure that mechanisms handle the privacy issues correctly.
- Mechanisms with other natural properties (besides SO, IC, IR, BB) may also be interesting in ATM.
- We treated the resource owner as an entity indifferent to the profit. A different line of work may investigate mechanisms that take the owner’s utility into consideration.

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