Incentive Design for Equitable Resource Allocation: Artificial Currencies and Allocation Constraints

Doctoral Consortium

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ABSTRACT

The proliferation of algorithmic decision-making systems in resource allocation applications has enabled the efficient allocation of scarce resources. However, in the pursuit of an efficient outcome, such systems often discriminate against some users who may be made disproportionately worse off. To address this concern, in this work, we aim to develop equitable allocation mechanisms that respect the often complex preferences of users and associated allocation constraints while catering to the needs of all groups of society. In particular, we will develop conceptual frameworks to embed fairness and equity constraints in designing resource allocation mechanisms for emerging transportation and labor market applications. Furthermore, we will devise artificial currency market mechanisms that ensure users have an equal opportunity to avail resources. The results of this research will help (i) catalyze support from multidisciplinary stakeholders at the intersection of economics and optimization, (ii) inform policymakers about how to improve regulation in transportation, labor, and artificial currency markets, and (iii) lay the groundwork to pilot the mechanisms to tackle important resource inequity challenges in real systems.

KEYWORDS

Market Equilibrium; Congestion Games; Traffic Routing; Artificial Currencies; Congestion Pricing; Fisher Markets; Labor Markets

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1 INTRODUCTION

The design of market mechanisms for scarce resource allocation is central to economic theory and has implications across applications from vaccine distribution to the allocation of roads to users. In the last several decades, algorithmic decision making systems have had an increased influence in the allocation of scarce resources and have demonstrated tremendous potential in improving the effectiveness of such market mechanisms. While existing tools to allocate scarce resources have proven effective in increasing system efficiency, as in the case of congestion pricing for road traffic mitigation, they are often of limited practical interest due to the resultant social inequity concerns (e.g., favoring wealthy individuals).

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The goal of this thesis is to address the inadequacy of existing resource allocation approaches by developing allocation mechanisms that cater to the needs of all groups of society while respecting the often complex preferences and constraints that arise in a range of applied resource allocation problems. To this end, we (i) go beyond traditional resource allocation approaches in traffic routing and labor market applications by embedding fairness and equity in the design of such allocation mechanisms, and (ii) develop practically deployable artificial currency based mechanisms to ensure that users have an equal opportunity to avail resources. The tools generated by this thesis will provide a general theoretical framework to reason about non-traditional resource allocation schemes, such as artificial currencies, to allocate limited resources. Furthermore, the results of this work will help in paving the way towards the design of allocation mechanisms that achieve a balance between multiple performance criteria, e.g., economic, equity and environmental goals, across a range of markets, including transportation, labor, and artificial currency markets.

2 CORE TECHNICAL APPROACH

In our pursuit of resource allocation approaches that mitigate the aforementioned inequity and fairness concerns of traditional mechanisms, we pursue two primary research thrusts. First, we study and design incentive mechanisms that induce self-interested users to collectively satisfy multiple performance criteria that are governed through allocation constraints. That is, we seek to characterize mechanisms that can feasibly implement an allocation meeting multiple performance desiderata through an alignment of user's incentives with the proposed allocation in both transportation and labor markets. Next, we investigate alternatives to traditional monetary pricing based allocation mechanisms through the study of artificial currency markets. In this context, we investigate generalizations of the classical Fisher market framework to the setting of online user arrival as well as the setting when agents have additional allocation constraints.

2.1 Fairness Constrained Incentive Design

We consider the design of equitable and fair resource allocation mechanisms in the context of (i) transportation applications, and (ii) labor markets. We now review the existing and future contributions of this thesis in both these markets in turn.

2.1.1 Transportation Markets. Our focus in transportation markets entails devising congestion pricing schemes that strike a balance between the efficiency and equity (and fairness) goals of sustainable transportation. In particular, we develop congestion pricing

schemes from two different perspectives. First, we consider the use of refunding of the collected toll revenues to the appropriate groups of users to tackle the equity concerns of congestion pricing [1]. The second approach entails the use of differential pricing schemes, wherein people can trade-off the inconvenience of obtaining a less desirable route with the higher cost of availing a more desirable one [2]. The differential pricing mechanisms we consider are schemes where an increase in travel time and discomfort to use a free, "externality minimizing" route is bounded, ensuring that less well-off individuals always have a free option with an acceptable level of quality.

While the results of [2, 3] pave the way for the design of equitable congestion-pricing schemes, significant practical challenges remain. Most notably, we assume centralized knowledge of user attributes, e.g., the values-of-time of users, in the design of our schemes. Since, in practice, this information is typically not available to a central planner, we consider the problem of *learning* the optimal tolls to set in the traffic network. To this end, we will harness the ever increasing availability of user data, e.g., their travel behavior, to better inform the appropriate tolls to set in the traffic network.

2.1.2 Labor Markets: In a recent line of work [4], we study labor markets, wherein firms have constraints over the types of workers they can hire to meet certain distributional objectives, e.g., increase the representation of minorities in the labor force through affirmative action policies. In such markets, we establish the efficiency of equilibrium arrangements, specified by an assignment and transfers between agents on the two sides of the market, and study the conditions on the constraint structure and agent preferences under which equilibria exist. In particular, we establish a strong connection between linear programming duality and the existence of equilibrium arrangements in such two-sided matching markets and also study their existence in settings when the substitutes condition may not hold. As future work, we will look to develop mechanisms that, in addition to guaranteeing the existence of market equilibria, are strategy-proof for agents on one side of the market, thereby aligning the agents' incentives with the proposed matching.

2.2 Equilibrium Theory in Artificial Currency Markets

The use of artificial currencies as an alternative means to allocate resources has gained traction in settings where payments are not allowed, such as the allocation of food to food banks [5] and the allocation of students to courses [6]. The absence of monetary transfers ensures that allocation decisions are not biased towards those with higher incomes and thereby artificial currencies open the door to ensuring an equal opportunity to all users to avail resources. A canonical model studied in the context of artificial currency based resource allocation is that of Fisher markets, wherein agents spend a budget of currency to buy goods that maximize their utilities, while producers sell capacity constrained goods in exchange for currency. However, classical Fisher markets (i) only consider two types of constraints, i.e., budgets of individual buyers and capacities of goods, and (ii) involve a complete information setting wherein the utilities of the buyers are known and all the transactions take place in a static market. These limiting assumptions make Fisher markets less amenable for resource allocation settings when agents have additional linear constraints [7] and when buyers arrive into the market sequentially with utilities that are not known *apriori* to the market designer. In this thesis, we broaden the applicability of artificial currency mechanisms by developing modified Fisher markets for these more complex settings.

Our technical approach towards the generalization of classical Fisher markets to the aforementioned settings has two primary components: (1) theoretical foundations regarding models of user behavior under additional allocation constraints and the dynamics of user arrival in an online variant of the Fisher market, and (2) algorithms for computing allocation strategies and market clearing prices for these more complex problem settings.

Theoretical Foundations: For the setting of Fisher markets with additional allocation constraints, we introduce a modified Fisher market and develop a new convex program analogous to Eisenberg-Gale's program [8] to compute equilibrium prices. We further study the properties of the corresponding market equilibria and establish conditions for its existence [9]. For the setting of online Fisher markets, we consider the setting when buyers enter the market sequentially and the goal of a central planner is to learn market clearing prices based on the observed buying behavior of users.

Algorithms and Guarantees: Building upon the aforementioned theoretical foundations, we will devise resource allocation algorithms for the above mentioned generalizations of Fisher markets. In the context of Fisher markets with additional allocation constraints, one of the major drawbacks of equilibrium computation using a social convex optimization problem is that it relies on the complete knowledge of human preferences. To overcome this concern, we devise distributed algorithms with fast convergence guarantees to the market equilibrium while *not* requiring any information on the utilities of the agents [9].

On the other hand, for online Fisher markets, we study data-driven price adjustment strategies, wherein prices are updated based on observed spending behavior of buyers. In particular, we plan to investigate both (i) local price adjustment methods, such as mirror descent, wherein prices are updated at each point in time a user arrives based solely on the consumption or selling behaviour of that user, and (ii) dynamic learning methods, wherein the prices are updated based on the entire history of observed user arrivals. To establish the correctness of these algorithms, we will investigate the difference between the social objective corresponding to the computed allocations and that of the optimal offline solution. In making this comparison, we will seek to obtain sub-linear regret guarantees of our developed algorithms for the online variant of Fisher markets.

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