The Segmentation-Thickness Tradeoff in Online Marketplaces*

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ABSTRACT

A core tension in the operations of online marketplaces is between segmentation (wherein platforms can increase revenue by segmenting the market into ever smaller sub-markets) and thickness (wherein the size of the sub-market affects the utility experienced by an agent). An important example of this is in dynamic online marketplaces, where buyers and sellers, in addition to preferences for different matches, also have finite patience (or deadlines) for being matched. We formalize this trade-off via a novel optimization problem that we term as ‘Two-sided Facility Location’: we consider a market wherein agents arrive at nodes embedded in an underlying metric space, where the distance between a buyer and seller captures the quality of the corresponding match. The platform posts prices and wages at the nodes, and opens a set of virtual clearinghouses where agents are routed for matching. To ensure high match-quality, the platform imposes a distance constraint between an agent and its clearinghouse; to ensure thickness, the platform requires the flow to any clearinghouse be at least a pre-specified lower bound. Subject to these constraints, the goal of the platform is to maximize the social surplus subject to weak budget balance, i.e., profit being non-negative. Our work characterizes the complexity of this problem by providing both hardness results as well as algorithms for this setting; in particular, we present an algorithm that for any constant $\epsilon > 0$ yields a $(1 + \epsilon)$ approximation for the gains from trade, while relaxing the match quality (i.e., maximum distance of any match) by a constant factor.

ACM Reference Format:

Reza Alijani, Siddhartha Banerjee, Sreenivas Gollapudi, Kostas Kollias, and Kamesh Munagala. 2019. The Segmentation-Thickness Tradeoff in Online Marketplaces. In *ACM SIGMETRICS Int’l Conference on Measurement & Modeling of Computer Systems (SIGMETRICS’19 Abstracts)*, June 24–28, 2019, Phoenix, AZ, USA. ACM, New York, NY, USA, 2 pages. <https://doi.org/10.1145/3309697.3331519>

1 INTRODUCTION

The basic algorithmic challenge facing a marketplace platform can be summarized as follows: it must decide *which buyer should match*

*This document is an extended abstract for [1]

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SIGMETRICS’19 Abstracts, June 24–28, 2019, Phoenix, AZ, USA

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ACM ISBN 978-1-4503-6678-6/19/06.

<https://doi.org/10.1145/3309697.3331519>

to which seller, at what time, and for what price and wage, in order to maximize some desired objective. Though this description has much in common with other mechanism-design problems in settings such as resource allocation and monopolist pricing problems, there are a few features unique to two-sided markets that make them particularly challenging.

Our work studies one such feature of two-sided markets – the tension between market segmentation and market thickness. At a high level, segmenting agents on both sides of a market into smaller sub-markets leads to better welfare and higher revenues in many settings; on the other hand, the quality of experience of an agent in a market improves when more agents are present on the other side. Ensuring both turns out to present severe computational challenges for the market maker in terms of pricing and scheduling policies. In particular, *our core algorithmic insight is that resolving the segmentation-thickness tradeoff in two-sided markets is intimately related to a classical ‘hard’ problem in combinatorial optimization: facility location.*

Before presenting this, however, we first present a natural setting that naturally exhibits the segmentation-thickness trade-off, and which forms the primary motivation for our work.

Dynamic Marketplaces with QoS Guarantees: Our motivating application is the design of a dynamic marketplace platform, and in particular, policies for pricing both buyers and sellers, and scheduling feasible matches, while providing quality of service (QoS) guarantees to the agents. To understand how this results in a segmentation-thickness tradeoff, it is useful to build up the setting piece-by-piece.

Pricing, matching and market segmentation: Consider first a simple two-sided market setting, where buyers and sellers are characterized by a *public type* and there is a single service they are interested in trading. Buyers have values, and sellers have costs, and these are drawn from known type-dependent distributions. For instance, on a platform like AirBnB, the type of a listing can represent some combination of geographic location and quality of room; on a freelancing platform, the type of a consultant can capture their skill set and the type of a task can capture its requirements; and so on.

Suppose we now incorporate dynamics as follows. Buyers and sellers belong to discrete types, and agents of any type arrive at a steady Poisson rate. Buyers accept prices that are lower than their value, and sellers accept wages that are higher than their costs, and the prices and wages set for different types determine the rates of arrival. We further assume buyer and seller types are located in a metric space. Typically, the buyer would be happy as long as the

seller a reasonable match with her requirements, so that there is an upper bound on the metric distance of any feasible match. We will use “type” and “node” interchangeably.

A policy for the platform is to (i) set a per-type price (for buyers) and wage (for sellers); and (ii) schedule feasible matches between the arriving buyers and sellers who accept the price/wage. The goal of this process can be to maximize social surplus, or revenue, or even more complex combinations such as maximizing surplus subject to a minimum revenue guarantee. Nevertheless, for all such objectives, finding the optimal policy is not difficult – in particular, it is given by a convex flow program with prices/wages set in a fashion to balance the rates of flow from buyers to sellers and maximize social surplus. Moreover, note that such a flow program formally encodes the idea of *market segmentation*.

Impatient agents and the role of thickness: Now consider what happens when buyers and sellers have a *patience level*. They observe the price/wage, and accept/reject it. If they accept, the platform may not immediately be able to match them because a feasible match may not exist at that very moment. This will cause the buyers and sellers to wait. However, if they are not matched by the time their patience expires, they will abandon the system. The pricing and scheduling policy of the platform needs to make sure the abandonment probability is very small, since this causes dissatisfaction with the platform.

Finding the optimal policy for scheduling matches under an abandonment constraint is a difficult stochastic control problem; however, a commonly-used class of policies which admits tractable analysis is one where the platform “pools” arriving demand and supply at close-by nodes, which correspond to clearinghouses for matching – we alternately refer to these as “facilities”. Demand and supply is probabilistically routed to facilities, and agents routed to a single facility are matched optimally. For such policies to have abandonment probability below a threshold, we show that two natural conditions are sufficient: (i) the rate of arrival of supply and demand to a facility are equal; and (ii) this rate is at least a certain threshold, so that agents find feasible matches with high probability, *i.e.*, the facility is sufficiently *thick*. In essence, the aim of the platform is to ensure that the time for finding a match is on average much smaller than the patience of any buyer or seller.

The above setting thus naturally encodes the segmentation-thickness tradeoff: on one hand, the convex flow problem tries to segment agent types into smaller flows in order to maximize the platforms’ objectives; on the other hand, the need to ensure sufficient thickness at the clearinghouses places limits on the optimization. Crucially, the addition of the thickness constraints destroys the underlying convexity of the problem, and makes it much more computationally challenging – this is brought out by relating this problem to the facility-location problem, as we do next.

1.1 From Two-Sided Markets to Facility Location

One of our contributions is the reduction of a natural class of stochastic control policies for the *dynamic* pricing and scheduling problem described above to a *static* problem of locating facilities in the metric space so that these facilities are sufficiently thick. In the resulting facility location problem, buyers and sellers flow

into nodes located in a metric space. The price (resp. wage) set at any buyer (resp. seller) node determines the volume of flow at that node. The platform needs to (i) open facilities in the metric space; (ii) assign prices and wages to each node; and (iii) probabilistically route the resulting flow to the open facilities so that the following service guarantees are satisfied:

- (1) **Quality of service guarantees:** The flow assigned to a facility is from supply and demand nodes within distance R . (This ensures any matched demand/supply is within distance $2R$.)
- (2) **Service availability guarantees:** Each facility needs to have *flow balance*, that is, equal amount of supply and demand is routed there. Further, there is a *lower bound* L on the flow routed to each facility, capturing the thickness constraint. As mentioned before, we show that these constraints arise from natural stochastic matching policies for dynamically arriving *impatient* agents.

The platform’s objective is to maximize the *gains from trade* or *social surplus*, which is total value of buyers *minus* total cost of sellers, subject to weak *budget balance*, meaning the platform has non-negative total profit. We term this optimization problem as *Two-sided Facility Location*. Such a facility location model enables us to abstract out the stochastic dynamics of scheduling with deadlines, and focus on studying the interplay between pricing and the service guarantee of finding good quality matches with high probability.

In summary, there is a three-way tension between the goals of maximizing surplus, platform profitability, and the service guarantees described above. Our problem formulation of *Two-sided Facility Location* captures this trade-off, and understanding the computational complexity of this problem is the main focus of this paper.

1.2 Our Results

Our main contribution is to show an approximation algorithm for *Two Sided Facility Location*. We present a new LP rounding framework that for any constant $\epsilon > 0$, achieves a $(1+\epsilon)$ approximation to the social surplus objective. It relaxes the distance bound constraint by a factor of 4, while preserving the budget balance constraint, as well as the flow balance and lower bound constraints at each facility.

We show that the surplus objective is NP-HARD to approximate to a factor $\alpha(L^\xi)$ for some constant $\xi > 0$, unless the distance bound is relaxed by at least a factor of 2.

ACKNOWLEDGMENTS

Reza Alijani is supported by NSF grants CCF-1408784 and CCF-1637397. Siddhartha Banerjee is supported by NSF grant DMS 1839346, ECCS-1847393, and the Army Research Office grant W911NF-17-1-0094. Kamesh Munagala is supported by NSF grants CCF-1408784, CCF-1637397, and IIS-1447554; and by an Adobe Data Science Research Award. We thank Sungjin Im and Janardhan Kulkarni for helpful comments on an earlier draft of this paper.

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