Title: Sparse and Efficient Rebalancing Network: Exploiting the Circadian Rhythm in Bicycle Sharing Systems

We study the use of volunteers as an alternative to rebalance bikes in a bicycle sharing system before the morning and evening peak hours. This work is motivated by the Bike Angels Program in New York’s Citi Bike system (c.f. Figure 1), in which bike angels are Citi Bike riders that improve the availability of bikes and docks for fellow riders and earn rewards along the way. In this system, stations that typically face shortage of bikes (resp. docks) during peak ride periods are identified as drop-off (resp. pick-up) stations and those stations which are neither drop-off nor pick-up stations are called neutral stations. The bike angels are given reward points when they take a bike from a pick-up station and return it to a drop-off or neutral station, or when they take a bike from a neutral station and return it to a drop-off station. For easier system management, we study how to design a sparse network in which the bike redistribution is only allowed between some station pairs, but is able to rebalance the bikes almost as well as the fully flexible network in which the bike redistribution is allowed between any station pairs.

This is similar to the classical transshipment network design problem often studied in the supply chain flexibility problem. Jordan and Graves (1995) observed that “a small amount of flexibility added in the right way can have virtually all the benefits of total flexibility” in several production systems. This insight was extended to transshipment network design, with the chaining structure being touted as the preferred sparse network to support transshipment flows, see Lien et al. (2011) for an approach to design the chaining structure.
Interestingly, the structure used by Citi Bike in its Angels program uses a different design philosophy (c.f. Figure 2). As such, we aim to understand which structure is better and try to understand how we can design a good structure by exploiting the “Circadian Rhythm” of transport demand in the city that leads to spatial and temporal mobility patterns of uneven bicycle usage.

![Figure 1 Bike Angels map in New York’s Citi Bikes](image)

**Figure 1 Bike Angels map in New York’s Citi Bikes**

![Figure 2 Graph Representation of Different Structures](image)

**Figure 2 Graph Representation of Different Structures**

We develop a distributionally robust method to design a static sparse network to support the re-distribution activities. The traditional process flexibility model, which is to develop production network to match capacities and demands, is used as a benchmark for performance comparison. Depending on the operating conditions, our method often produces a hybrid structure that outperforms both the long chains and the Bike Angels
structure. We use this technique to develop a near optimal rebalancing network for a system with 60 stations, using a data set from the Hubway system in Boston. Our results show that using a much smaller set of arcs (around 15%) to support the rebalancing activities of the volunteers in the system only causes a small loss (less than 4%) of the performance efficiency.

### Table 1 Out-sample Simulation Performance under Fully and Sparse Structure for Hubway BSS

<table>
<thead>
<tr>
<th></th>
<th>Fully Flexible Structure</th>
<th>Traditional Process Flexibility Model</th>
<th>Performance Gap (%)</th>
<th>Our Model with Limited Transshipment</th>
<th>Performance Gap (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>115.8988 (3540-arc)</td>
<td>73.2188 (120-arc)</td>
<td>36.83%</td>
<td>70.9700 (120-arc)</td>
<td>38.77%</td>
</tr>
<tr>
<td>#2</td>
<td>115.8988 (3540-arc)</td>
<td>93.5288 (240-arc)</td>
<td>19.30%</td>
<td>98.3450 (240-arc)</td>
<td>15.15%</td>
</tr>
<tr>
<td>#3</td>
<td>115.8988 (3540-arc)</td>
<td>109.4250(480-arc)</td>
<td>5.59%</td>
<td><strong>111.6000 (480-arc)</strong></td>
<td><strong>3.71%</strong></td>
</tr>
<tr>
<td>#4</td>
<td>115.8988 (3540-arc)</td>
<td>112.4238(720-arc)</td>
<td>3.00%</td>
<td>115.3650 (720-arc)</td>
<td>0.46%</td>
</tr>
</tbody>
</table>

In other words, when restricting the work of the Angels to only a small but properly chosen subset of arcs in the network, the system can still perform almost as well as the fully flexible system, in which bikes can be moved between any pair of stations based on actual usage. The models proposed in our paper provides a distributionally robust method to identify such a small but properly chosen subset of arcs. This simplifies the complexity of bike rebalancing operations dramatically on the ground, with very little impact on the system's service performance.

**References**
