Solution approaches and incentive schemes in collaborative logistics planning
(joint work with Margaretha Gansterer)

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Sharing Economy

A recent paradigm shift can be observed towards an economy in which **resources** and **capacities** are **shared** between customers or firms who otherwise compete.

- INFORMS TSL workshop in Vienna, July 2019
- SI “transportation in sharing economy” in *Transportation Science*

Two main streams of research/application:

- Customers share durable goods rather than buying them (e.g. bike sharing, car sharing, ride sharing, ...)
- Firms share resources to fulfill their operations more efficiently (e.g. collaborative vehicle routing, ...)
Outline

• Collaborative Logistics - Motivation
• Focus on Collaborative Vehicle Routing
• Five Steps of Decentralized Collaborative Vehicle Routing with Combinatorial Auctions
  ✓ Request Selection
  ✓ Bundle Generation
  ✓ Bidding
  ✓ Winner Determination
  ✓ Profit sharing
• Strategic Behavior
• Outlook on Other Logistical Planning Problems
Collaborative Logistics – Intro & Motivation

• In horizontal collaborations, carriers partners in the same level of the supply chain collaborate and form coalitions in order to perform parts of their logistics operations jointly

• Horizontal collaboration means e.g. that by exchanging transportation requests among each other, they can operate more efficiently and in a more sustainable way

• Transportation is one of the biggest contributors of CO₂ emissions (GHG)

• Aim not only at reduced emissions of harmful substances, but also reduced road congestion and noise.
Collaborative Logistics – Vehicle Routing

• By collaboration we refer to all kinds of cooperation, which are intended to increase the efficiency of logistics operations.

• We use the terms collaboration and cooperation interchangeable.

• In the literature, partly collaboration is used for some “strong” type of cooperation. However, the boundary between them is vague.
Types of cooperation

In our survey,


and update


we identify 3 major streams of research:

1. Centralized collaborative planning
   (often not clear what is different from normal vehicle routing)
2. Decentralized planning with combinatorial auctions
   (focus of this presentation)
3. Decentralized planning with other exchange mechanisms
   (e.g. pairwise exchange of requests)
Combinatorial Auctions

- In a combinatorial auction (CA) participants can place bids on combinations of discrete items (bundles, packages), rather than individual items or continuous quantities.

CA have been used for
- truckload transportation
- bus routes
- industrial procurement
- allocation of radio spectrum for wireless communications

- In „less than truckload“ (LTL) transportation and vehicle routing, application of CA still active research area - many open questions
- Even more so in other logistical problems
Combinatorial Auctions in LTL Vehicle Routing

- Why are **bundles** important in context of Vehicle Routing?
  - Pickup (+) and delivery (-)
  - C4 and C5 alone are not attractive for some carrier.
  - If both requests are won, this bundle can be attractive
  - Exposure problem
Combinatorial Auctions

- Mathematically, the main step in CA is typically the **winner determination problem**: Given a set of bids on items and bundles, find an allocation of items/bundles to bidders that maximizes the auctioneer’s revenue (coalition gain).
- Mathematically a CA is a **set partitioning problem** (if all items need to be allocated), which is NP-hard, and is difficult to solve for large instances.
5 Steps of CA in Collaborative Vehicle Routing

1. **Request selection:**
   Carriers decide which requests to put into the auction pool

2. **Bundle generation**
   The auctioneer generates bundles of requests and offers them to the carriers

3. **Bidding:**
   Carriers place their bids for the offered bundles

4. **Winner Determination:**
   Auctioneer allocates bundles to carriers based on their bids (combinatorial auction, SPP)

5. **Profit sharing:**
   collected profits are distributed among carriers
1. Carriers decide which requests to put in auction pool
1. Carriers decide which requests to put in auction pool

Possible procedures:

a) Carriers decide based on the aspect which request are most expensive to fulfill (most remote, ...)
   solve the **Profitable PDP** (using VNS)
   
1. Carriers decide which requests to put in auction pool

Possible procedures:

b) Carriers do **not** know the requests of competitors, but do know some characteristics (e.g. the depot location) of competitors and use this info to provide attractive requests/bundles to competitors → yields better collaboration profits in the CA


Coalition profit is higher (than for profitable PDP selection), if carriers select requests which are (far away from their own depot and) **close to some competitor‘s depot**.

*No info on requests of the competitors needed, no need of cost structure of competitors needed*

*But prisoner’s dilemma!*
Prisoner’s dilemma in request selection

- 2 people jointly commit a crime, are caught together
- are interrogated in separate rooms
- If both confess/betray → both medium penalty (2)
- If both deny/stay silent → both small penalty (1)
- If one denies and other confesses
  The one who confesses (crown witness) → no penalty (0)
  The one who denies → high penalty (3)

Here:
- Confess (just offer junk)
- Deny (offer interesting requests)
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5. **Profit sharing:** collected profits are distributed among carriers
2. Auctioneer generates bundles of requests

- (A1), (B2), (B3), (C4), (C5)
- (A1, B2), (A1, B3), (A1, C4), (A1, C5), (B2, B3), (B2, C4), (B2, C5), (B3, C4), (B3, C5), (C4, C5)
- (A1, B2, B3), (A1, B2, C4), (A1, B2, C5), (B2, B3, C4), ...
- (A1, B2, B3, C4), (A1, B2, B3, C5), ...
- (A1, B2, B3, C4, C5)

- If $n$ requests are put in auction pool
- $2^n - 1$ bundles
Bundle Generation: are all bundles needed?

• Selection using a GA based on **density, isolation, and tour length**:
• Numerical study with 12 requests → up to 4095 bundles


<table>
<thead>
<tr>
<th>Pool size</th>
<th>Avg. result</th>
<th>Avg. runtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>4095</td>
<td></td>
<td>47.6</td>
</tr>
<tr>
<td>50</td>
<td>-22.3%</td>
<td>1.1</td>
</tr>
<tr>
<td>100</td>
<td>-13.3%</td>
<td>1.3</td>
</tr>
<tr>
<td>200</td>
<td>-8.2%</td>
<td>2.3</td>
</tr>
<tr>
<td>300</td>
<td>-6.9%</td>
<td>3.6</td>
</tr>
<tr>
<td>500</td>
<td>-5.2%</td>
<td>5.5</td>
</tr>
</tbody>
</table>

• With only 500 bundles (90% less bundles and CPU time), the coalition profit only drops by 5%
Objective function in the GA for bundle generation:

- Good bundles should have a high value of

  \[ \text{isolation} \times \text{density} / \text{tourlength} \rightarrow \text{max} \]

- **Density** = avg direct travel distance / max distance to center of gravity

- **Isolation** =
  min distance to other bundle / max radius of these bundles
Who Should Build Bundles (and How Many)?

We suggest: bundles should be built by auctioneer


Compare

- **Bundles built by auctioneer:** just 100, 200 or 500 bundles are built out of all 4000 (for 12 requests) or 32000 (for 15 requests) possible bundles

- Alternative: **bundles built by carriers:** each one evaluates all (4000 or 32000) bundles, and bids on 200 or 500 of most attractive ones
Who Should Build Bundles (and How Many)?

Results of


<table>
<thead>
<tr>
<th>#requests</th>
<th>Auctioneer bundles</th>
<th>Carrier bundles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#bundles</td>
<td>APCI</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>42.01</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>45.37</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>46.49</td>
</tr>
<tr>
<td>15</td>
<td>12</td>
<td>45.72</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>50.58</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>51.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>12</td>
<td>42.40</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>55.22</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>53.89</td>
</tr>
</tbody>
</table>

- With 100 auctioneer bundles much better results than with 1500 carrier bundles. Why? Cherry picking…
5 Steps of CA in Collaborative Vehicle Routing

1. **Request selection:** Carriers decide which requests to put into the auction pool
2. **Bundle generation** The auctioneer generates bundles of requests and offers them to the carriers
3. **Bidding:** Carriers place their bids for the offered bundles
4. **Winner Determination:** Auctioneer allocates bundles to carriers based on their bids (combinatorial auction, SPP)
5. **Profit sharing:** collected profits are distributed among carriers
3. Carriers place their bids for the offered bundles

- For each of the (up to) $2^n-1$ bundles, each carrier has to determine,
  1. Whether he has enough capacity to introduce this in routes with the remaining requests
  2. What the marginal insertion costs are

- Solve $2^n-1$ np-hard VRPs (or less if only a subset of bundles is offered)
Computation of Bids for the Offered Bundles

Possibilities for computing/approximating the marginal (insertion) cost

1. Just use cheapest insertion and 2-opt
2. Reoptimize PDP routes (GA for larger instances)

Result of combinatorial study in


- Option 1 gives on average about 10% worse results for the VRP/PDP (marginal cost of the bundle for the carrier)
- TSP: For the result of the CA, the difference in collaboration gain is negligible
- VRP: better bidding methods important
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4. Winner Determination Problem (WDP)

CA: Auctioneer allocates bundles to carriers based on their bids
WDP: Combinatorial Auction

- $C$: set of bidders/carriers, $c \in C$
- $R$: set of requests, $r \in R$
- $B$: set of offered bundles
- $p_{bc}$: price carrier $c$ is willing to pay for bundle $b$
- $W_{br}$: parameter indicating whether request $r$ is included in bundle $b$ or not
- $Q_{bc}$: parameter indicating whether carrier $c$ submitted a bid for bundle $b$ or not
- $v_{bc}$: decision variable indicating whether bundle $b$ is allocated to carrier $c$ or not
WDP: Combinatorial Auction

\[
\begin{align*}
\max & \sum \sum p_{bc} v_{bc} \\
\sum & v_{bc} \leq 1 \quad \forall c \in C \\
\sum & v_{bc} \leq 1 \quad \forall b \in B \\
v_{bc} & \leq Q_{bc} \quad \forall b \in B, c \in C \\
\sum \sum & v_{bc} W_{br} = 1 \quad \forall r \in R \\
v_{bc} & \in \{0, 1\} \quad \forall b \in B, c \in C
\end{align*}
\]
4. Winner Determination Problem

- NP hard set partitioning problem
- “Easy“ after reduction of number of bundles as demonstrated
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5. Profit sharing

- Total driving distance has been reduced:

- Before

- Collected profits are distributed “fairly” among the carriers
5. Profit Sharing

- Collected profits are distributed “fairly” among the carriers
- What is fair?
- E.g. Shapley value requires more info than available
- Simple rules: Equal share, or proportional to number of exchanged requests
- Is profit sharing necessary? Is it legal?
The Problem of Strategic Behavior

So far in CA for TL and LTL transportation, it has been assumed that carriers act truthful:

• All follow the same (agreed upon) rule in request selection (e.g. based on isolation and density)

• All place the „correct“ bid values (marginal cost of insertion)

• Strategic behavior: what if carries do not act truthful (e.g. what if carriers do not place the „correct“ bids)

• How can you make them act truthful?
The Problem of Strategic Behavior


- Specific problems here:
  - **Double auction**: potential buyers submit their bids and potential sellers simultaneously submit their ask prices
  - **Dual auction**: Typically, carriers are buyers and sellers at the same time
  - **Costs/rewards** for requests outsourced/insourced are not independent from each other – necessary to bid on combined bundles (requests outsourced, requests insourced)
The Problem of Strategic Behavior

Investigate **desirable properties**

- **IC**: Incentive compatible (Bidding true costs should be Nash equ.)
- **IR**: Individual rational (No one is worse off participating)
- **EF**: Efficient (Maximize value creation from exchange)
- **BB**: Budget balanced (No loss for auctioneer)

Requirements are **incompatible**

- Myerson/Satherthwaite (1982) IC&EF → Subsidy needed (no BB)
- Wurman et al. (1989) same for double-sided auctions
Focus on IC ⇒ VCG mechanism

• Second price sealed bid auction
Vickery auction (VCG, Vickery, Clark, Groves)

• Example: you are willing to pay 200 € for an item
In first price auctions you have an incentive to bid less

• If you hope that second highest bid is around 100, you bid a bit more than 100

Second price sealed bid auction (Ebay):

• You can safely bid 200 € because – if you win – you only pay the value of the second highest bid (e.g. 100 €) [+ 0.50 €]

• If you bid less, you never pay less, you only decrease the probabilty of winning   [Of course you never bid more]

• VCG therefore IC: optimal to bid “real value”

• “with your bid you cannot influence how much you pay”
VCG mechanism in our case

• Second price difficult to compute (no one else can place a bit on exactly this bundle (insourced, outsourced requests)
• Note that each player has a monopoly over outsourced requests
• Auction theory tells you to compute an artificial second price via marginal contribution of each player:

Compute marginal contribution of each bidder $i$:
• Total coalition profit $Z^*$ (outcome of CA)
• “second price”: delete all bids of bidder $i$ and run CA again
• Results in coalition profit $Z_i [\leq Z^*]$

Reduce the bid value of each bidder (first price) by this marginal contribution $Z^* - Z_i$
VCG mechanism in our case

Compute marginal contribution of each bidder $i$: $Z^* - Z_i$

$p_i$ ... price player $i$ is willing to pay for his winning bid

Player $i$ only pays “second price” $p_i - (Z^* - Z_i)$

- This can be negative even if $p_i$ is positive
- Note that this “second price” is independent of $p_i$ since in/decreasing $p_i$ by $\varepsilon$ will in/decrease $Z^*$ by $\varepsilon$
- Hence IC
- If the price is reduced by less than marginal contribution, his payment depends on the bid and IC is lost
VCG second price - Example

<table>
<thead>
<tr>
<th>Cost</th>
<th>Bidder A</th>
<th>Bidder B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Request A1</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Request B1</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Possible bids of bidder A:
- \( b_1 = 2, S_1 = \{A1\}, T_1 = \{B1\} \) ... cost reduction of 2
- \( b_2 = 5, S_2 = \{A1\}, T_2 = \{\} \) ... cost reduction of 5
- \( b_3 = -3, S_3 = \{\}, T_3 = \{B1\} \) ... cost increase of 3

Possible bids of bidder B:
- \( b_4 = 3, S_4 = \{B1\}, T_4 = \{A1\} \) ... cost reduction of 3
- \( b_5 = 4, S_5 = \{B1\}, T_5 = \{\} \) ... cost reduction of 4
- \( b_6 = -1, S_6 = \{\}, T_6 = \{A1\} \) ... cost increase of 1

Notation:
- \( S = \{\text{outsourced req.}\} \)
- \( T = \{\text{insourced req.}\} \)

Optimal solution
- \( x_1 = x_4 = 1 \)

Coalition gain \( Z^* = 5 \)
**VCG second price - Example**

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<tr>
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<td>5</td>
<td>1</td>
</tr>
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<td>Request B1</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

If either player drops out, only trivial solution possible: all \( x_i = 0 \); Coalition gain \( Z_i = 0 \)

Second price (VCG) payment would be

\[
VCG \text{ payment} = (\text{value of accepted bid}) - (Z^* - Z_i)
\]

VCG payment to bidder A = \( b_1 - 5 = 2 - 5 = -3 \)

VCG payment to bidder B = \( b_4 - 5 = 3 - 5 = -2 \)

Both bidders receive payments (in VCG scheme) even though they profit from exchange and would be willing to pay for it (in first price scheme)

Optimal solution
\[
x_1 = x_4 = 1;
\]

Coalition gain \( Z^* = 5 \)
VCG not BB

- Auctioneer makes a loss -> high participation fee needed
- Compare standard VCG approach with more complicated team bidder (TB) approach
- \( TB_i \) of bidder \( i \) = set of all bidders for whom no bids are accepted once bidder \( i \) is excluded
- In the above example, \( TB_A = \{A, B\} \), \( TB_B = \{A, B\} \).
- Payment to each \( TB_i = \Sigma \) winning bids in \( TB_i \) - \( (Z^* - Z) \)
- This has to be done for all bidders \( i \) - can be shown to be IC
- Bidders can be part of several \( TB \) → set of linear equations to obtain individual payments to bidders
- Same number of equations as bidders, but can be dependent
- IR can be violated
VCG not BB

Numerical simulation with many instances
• **Ex ante** (before participation fee), VCG is IR, TB not always IR
• **Ex post** (after participation fee), both VCG and TB not always IR

<table>
<thead>
<tr>
<th>Instance</th>
<th>VCG</th>
<th>TB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IR</td>
<td>IR</td>
</tr>
<tr>
<td>O1</td>
<td>0%</td>
<td>5%</td>
</tr>
<tr>
<td>O2</td>
<td>0%</td>
<td>35%</td>
</tr>
<tr>
<td>O3</td>
<td>0%</td>
<td>35%</td>
</tr>
</tbody>
</table>

Instance types: O1: clustered, O2: medium, O3: large overlap
• **After participation fee, TB less violations of IR than VCG**
Outlook 1

Still many open questions

• **Is IC worth the price?** Look for other mechanisms that are not IC but have other nice properties

Maybe carriers are willing to **reveal some information** (e.g. number of requests in a certain grid cell) – does that help?

Outlook 2

- **Real world applications** of collaborative vehicle routing or cooperative planning in production and logistics

- Ideas for “sharing economy”, collaborative planning in **other areas of SCM**

- Where can **collaborative auctions** be used, where do we need to resort to **other exchange mechanisms** (e.g. repeated pairwise exchange with random matching)
Alternative Example: Collaborative Lotsizing


- Example of bill-of-materials (BOM)
- Several BOM levels
- Some items are "compulsory", i.e. only one producer available
- Others are *concurrent* (several alternative producers)
Alternative Example: Collaborative Lotsizing

Synergies (i.e. percentage cost reductions) if one agent can perform "related" operations together.

Related e.g.
- If same BOM level (e.g. 12 and 13)
- Or immediate predecessor/successor relation (e.g. 1 and 12)
Alternative Example: Collaborative Lotsizing

- Each operation must be assigned to exactly one agent.
- No sensitive information (setup cost, holding cost, capacities, …) should be revealed.
- Problem: exact costs cannot be computed from only knowing the assignments, but also production/lotsizing decisions of the upstream agents needed.
- A3 can only evaluate green assignment solution of lotsizing decisions of upstream agents A1 and A2 are known.

- CA not possible?
- Iterative procedure
- Pairwise exchange
- Better than previous approaches
- Not fully satisfactory