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 mains streams od 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 $\mathbf{CO_2}$ **emissions** (GHG)
- Aim not only at reduced emissions of harmful substances, but also reduced **road conges-tion** 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,

- Gansterer, M., Hartl, R.F. (2018), *Collaborative Vehicle Routing*. **European Journal of Operational Research**, 268, 1–12

and update

- Gansterer, M., Hartl, R.F. (2020), *Shared resources in collaborative vehicle routing,* **TOP**, issue 1, to appear.

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.

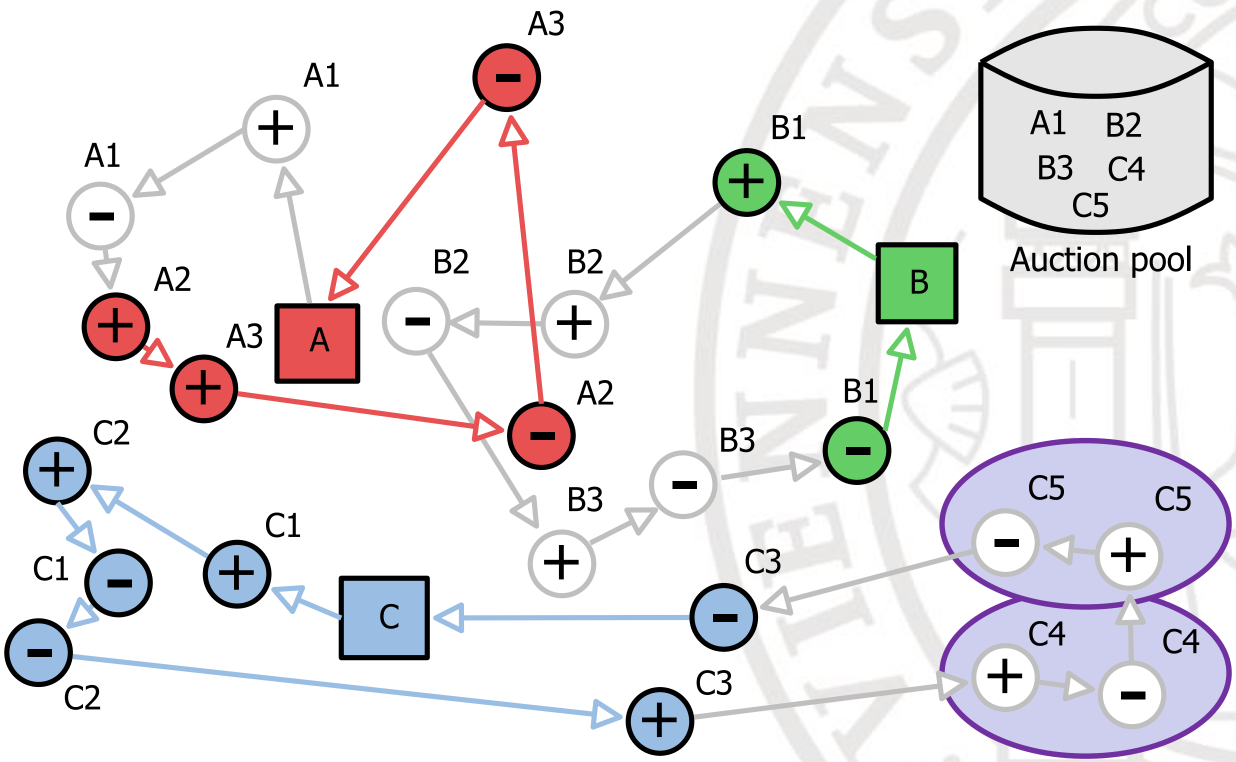
CA have been used for

- 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

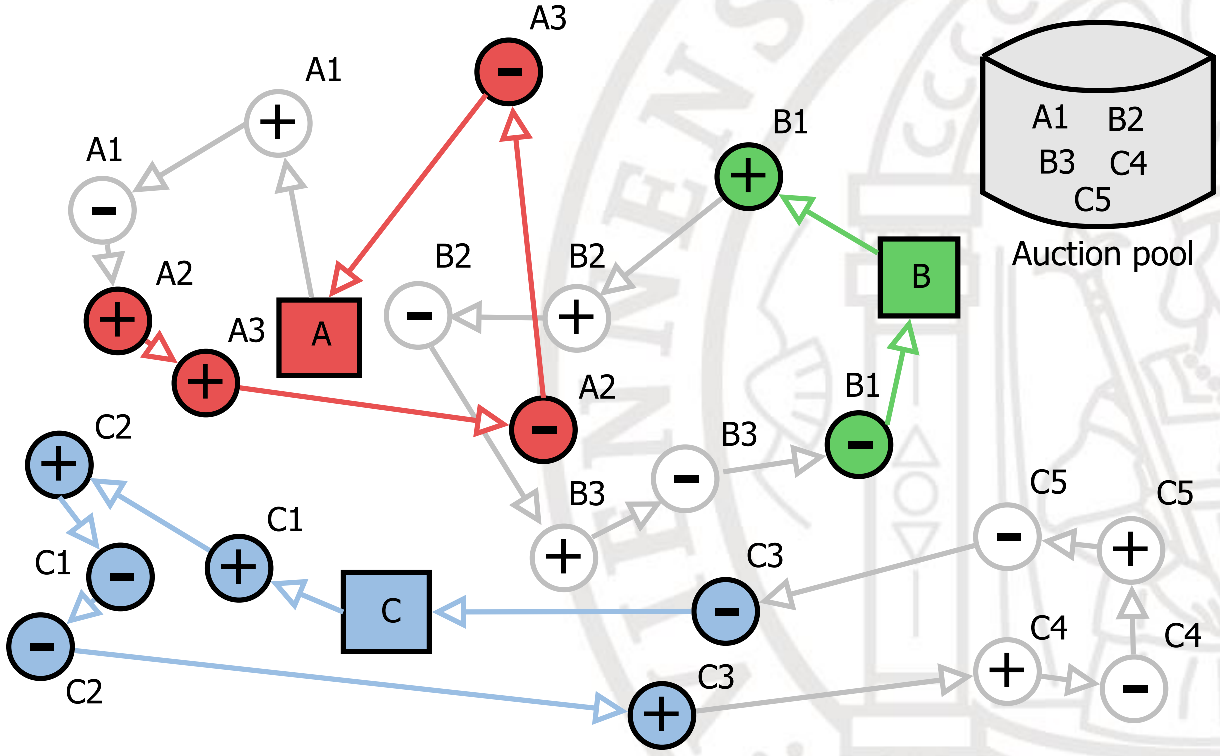
- Mathematically, the main step in CA is typically the **winner determination problem:**
- Given a set of bids on items and bundles, find an allocation of items/bundles to bidders that maximizes the auctioneer’s revenue (coalition gain)
- Mathematically a CA is a **set partitioning** problem (if all 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

- ***Berger, S., Bierwirth, C.*** *(2010): Solutions to the request reassignment problem in collaborative carrier networks. Transportation Research Part E, 46, 627-638.*

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

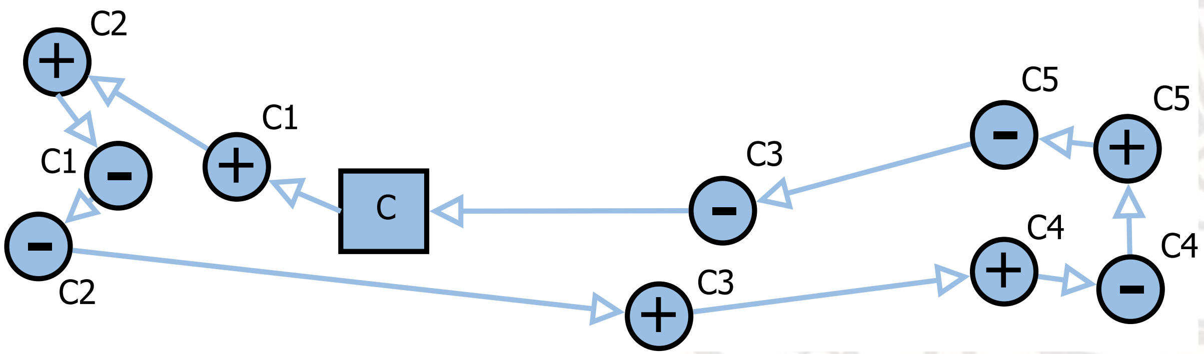


1. Carriers decide which requests to put in auction pool

Possible procedures:

a) Carriers decide based on the aspect which request are most expensive to fulfill (most remote, …)
solve the ***Profitable PDP*** (using VNS)

- *Gansterer, M., Kücüktepe, M., Hartl, R.F. (2017), The multi-vehicle profitable pickup and delivery problem.* ***OR Spectrum*** *39, pp. 303–319.*



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

- *Gansterer, M., Hartl, R.F. (2016), Request evaluation strategies for carriers in auction-based collaborations.* ***OR Spectrum****, 38 (1), pp. 3-23.*

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 !

Maybe skip this

Prisoner‘s dilemma in request selecion

- 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)

B A	B stays silent	B betrays
A stays silent	-1 -1	0 -3
A betrays	-3 0	-2 -2

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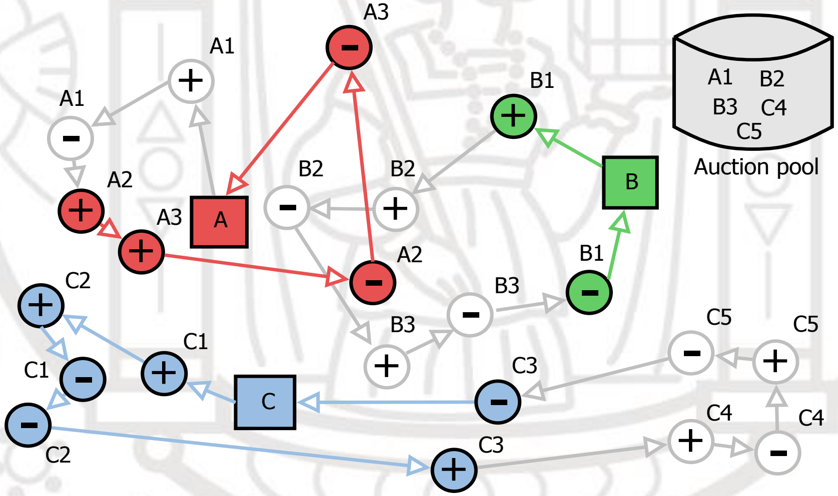
2. Auctioneer generates bundles of requests

- (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



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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
  - Gansterer M., Hartl R.F. (2018), *Centralized bundle generation in auction-based collaborative transportation*. **OR Spectrum** 40: 613–635

Pool size	Avg. result	Avg. runtime
4095		47.6
50	-22.3%	1.1
100	-13.3%	1.3
200	-8.2%	2.3
300	-6.9%	3.6
500	-5.2%	5.5

- With only 500 bundles (90% less bundles and CPU time), the coalition profit only drops by 5%

Maybe skip this

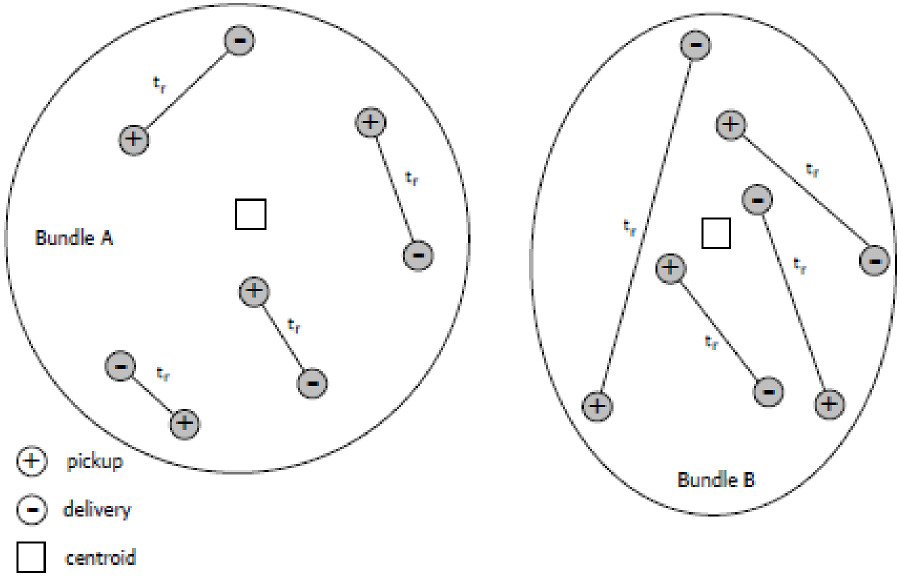
Objective function in the GA for bundle generation:

- Good bundles should have a high value of

isolation * density / tourlength → 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

- *Gansterer, M., Hartl, R.F.,* Sörensen, K. (2019*), Pushing frontiers in auction-based transport collaborations,* **Omega***,* Available online 27 February 2019.

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

- *Gansterer, M., Hartl, R.F.,* Sörensen, K. (2019*), Pushing frontiers in auction-based transport collaborations,* **Omega***,* Available online 27 February 2019.

	1V			
#requests	Auctioneer bundles		Carrier bundles	
	#bundles	APCI	#bundles	APCI
12	100	42.01	600	21.03
	300	45.37	1500	31.19
	500	46.49		
15	100	45.72	600	7.97
	300	50.58	1500	15.28
	500	51.79		

	MV			
#requests	Auctioneer bundles		Carrier bundles	
	#bundles	APCI	#bundles	APCI
15	100	42.40	600	7.64
	300	55.22	1500	11.49
	500	53.89		

- 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
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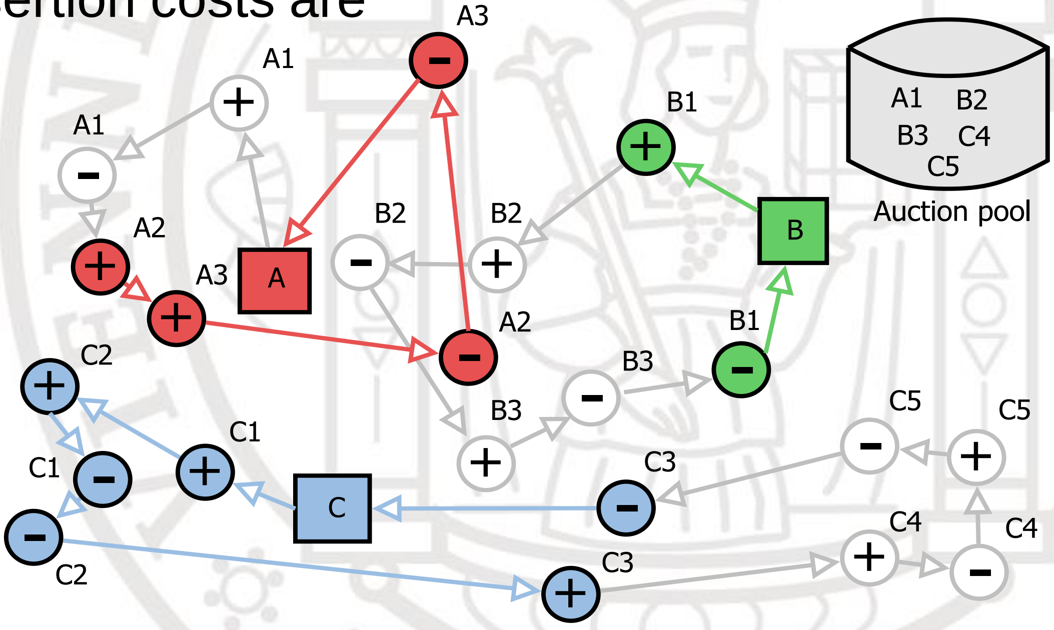
5. **Profit sharing**: collected profits are distributed among carriers

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)



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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

- *Gansterer, M., Hartl, R.F.,* Sörensen, K. (2019*), Pushing frontiers in auction-based transport collaborations,* **Omega***,* Available online 27 February 2019.

- 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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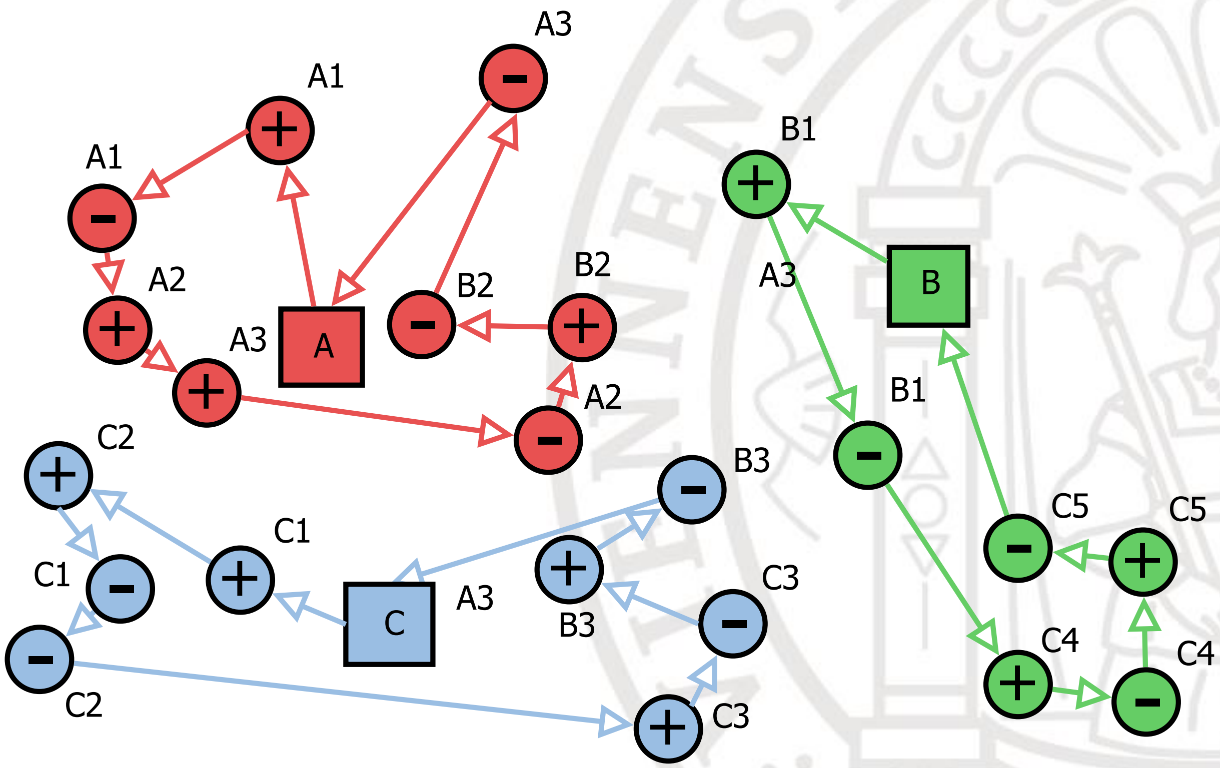
4. Winner Determination Problem (WDP)

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

$$max \sum_c \sum_b p_{bc} v_{bc}$$

$$\sum_b v_{bc} \leq 1 \qquad \forall c \in C$$

$$\sum_c v_{bc} \leq 1 \qquad \forall b \in B$$

$$v_{bc} \leq Q_{bc} \qquad \forall b \in B, c \in C$$

$$\sum_b \sum_c v_{bc} W_{br} = 1 \qquad \forall r \in R$$

$$v_{bc} \in \{0, 1\} \qquad \forall b \in B, c \in C$$

4. Winner Determination Problem

- NP hard set partitioning problem
- “Easy“ after reduction of number of bundles as demonstrated

5 Steps of CA in Collaborative Vehicle Routing

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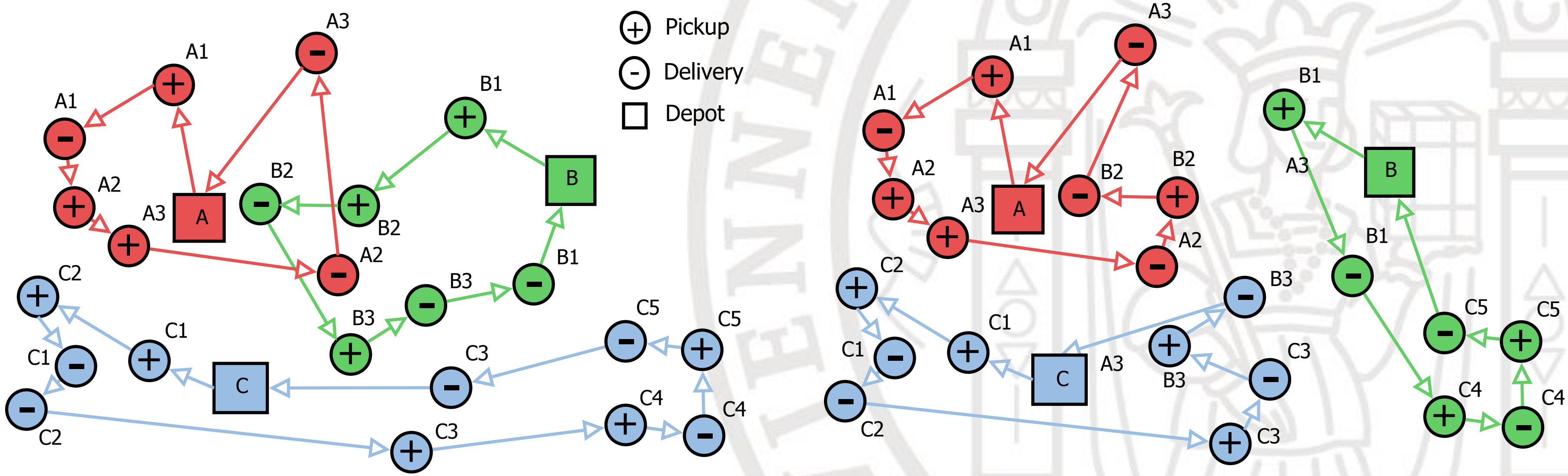
5. Profit sharing

- Total driving distance has been reduced:

- Before

After



- 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

- Gansterer, M., Hartl, R.F., Vetschera, R. (2018), *The cost of incentive compatibility in auction-based mechanisms for carrier collaboration*. **Networks**, published online 27 June 2018.

- 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 vale 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" $\boldsymbol{p_i - (Z^* - Z_i)}$

- *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 ε will in/decrease Z^* by ε***
- ***Hence IC***
- If the price is reduced by less than marginal contribution, his payment depends on the bid and IC is lost

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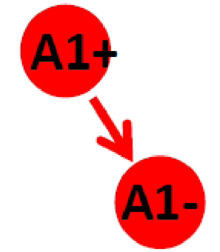
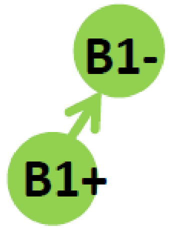


B

VCG second price - Example

A

Cost	Bidder A	Bidder B
Request A1	5	1
Request B1	3	4



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 = {outsourced req.},

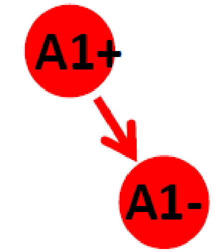
T = {insourced req.}

Optimal solution

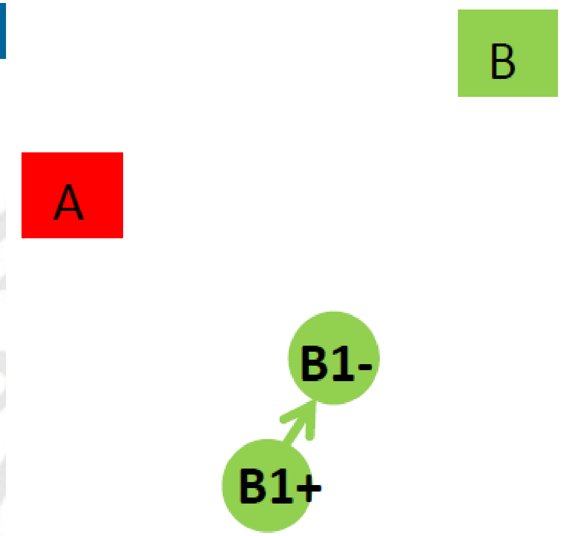
$x_1 = x_4 = 1;$

Coalition gain Z* = 5

Probably skip this



VCG second price - Example



Cost	Bidder A	Bidder B
Request A1	5	1
Request B1	3	4

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 payment = (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 $Z^* = 5$

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Probably skip this

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 = Σ winning bids in TB_i - (Z^*-Z_i)
- 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***

Probably skip this

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**

	VCG			TB		
Instance	IR	Rel loss	IR ex post	IR	Rel loss	IR ex post
O1	0%	1,5%	52,5%	5%	0,4%	5,0%
O2	0%	4,9%	42,5%	35%	2,6%	35,0%
O3	0%	7,5%	35,0%	35%	2,3%	35,0%

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?

- Gansterer, M., Hartl, R.F., Savelsbergh, M. (2019), *The value of information in auction-based carrier collaborations*, under revision in IJPE

Outlook 2

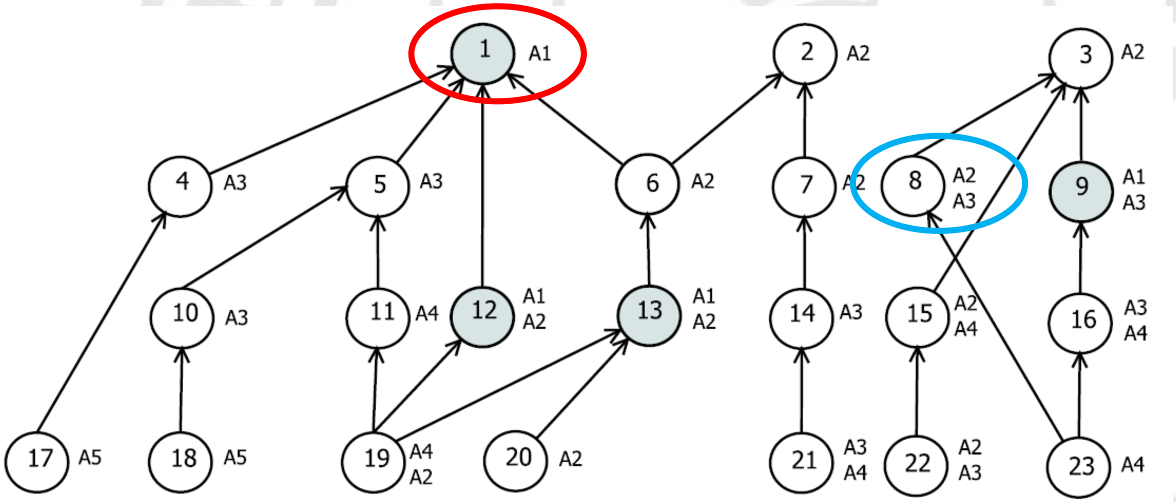
- ***Real world applications*** of collaborative vehicle routing ot cooperative planning in production and logistics

- 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

- Gansterer, M., Hartl, R.F. (2019), *The collaborative multi-level lot-sizing problem with cost synergies*. **International Journal of Production Research**, Published Online: 04 Mar 2019

- 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)

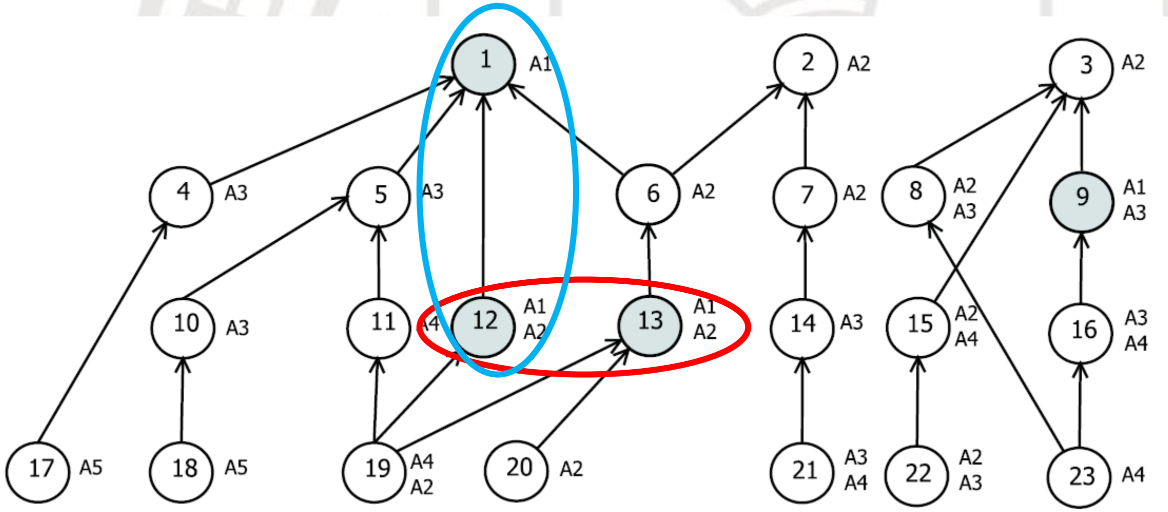


Alternative Example: Collaborative Lotsizing

Synergies (i.e. percentage cost reductions) if one agent can perfors „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, cpacities, …) should be revieled
- 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 assigment 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