Efficient solutions for the Green Vehicle Routing Problem with Capacitated Alternative Fuel Stations

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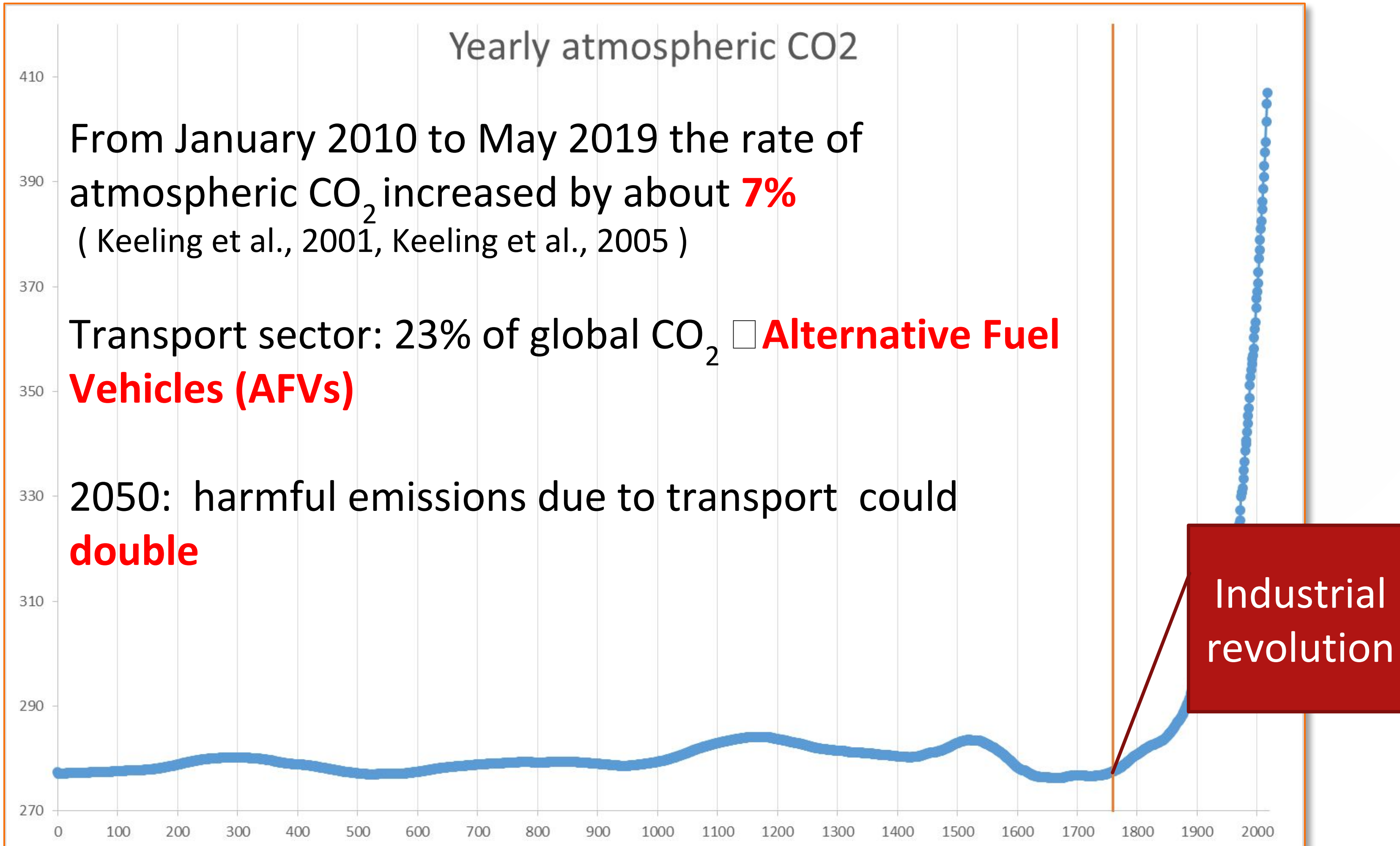
Agenda

- Introduction and motivation
- State of the art
- Algorithmic proposal
- Preliminary experimental results
- Conclusions and future work

Introduction



From January 2010 to May 2019 the rate of atmospheric CO_2 increased by about **7%**
(Keeling et al., 2001, Keeling et al., 2005)

Transport sector: 23% of global CO_2 □**Alternative Fuel Vehicles (AFVs)**

2050: harmful emissions due to transport could **double**

Source: www.co2.earth

Introduction

- **Advantages**:
  - reduction of harmful emissions
  - lower both kilometric and operating cost (i.e., operating cost of a conventional diesel truck is about **$0.23/miles** vs the **$0.09/miles** of an electric engine truck. [Feng & Figliozzi, 2012]).
  - possibility of reaching also **Limited Traffic Zones**

Introduction

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  - possibility of reaching also **Limited Traffic Zones**
- **Disadvantages**:
  - limited driving range: stops at **Alternative Fuel Stations** (AFSs) during trip
  - poor distribution of the AFSs on the territory

A priori route stops at AFSs

Green Vehicle Routing Problem

- Introduced by **Erdogan & Miller-Hooks, TRE 2012**

Routing a fleet of AFVs based at a common depot to serve a set of customers minimizing their total travel distance.

Along the trips, stops at AFSs (even more than once) and each time each AFV is fully refueled

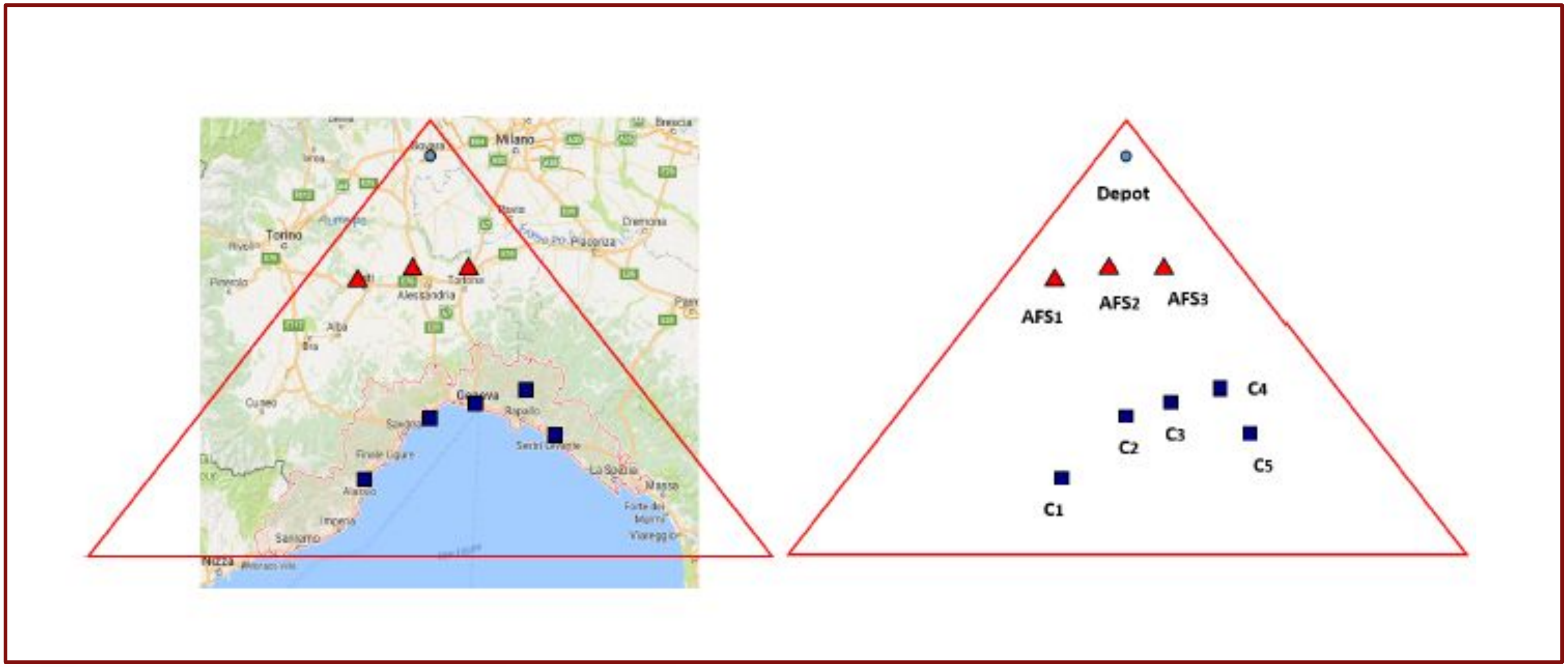
Green Vehicle Routing Problem

- **Assumptions:**
  - Available AFVs: m
  - Maximum route duration: T_{max}
  - Maximum driving range: D_{max}
  - Service time of each customer *i*: p_i
  - Fueling time at each AFS *s*: p_s independently of the actual tank level of the AFV
  - **Unlimited number** of AFVs can simultaneously fuel at the same AFS

- A realistic version of G-VRP was introduced by **Bruglieri, Mancini, Pisacane, COR 2019** in which each station has a limited capacity

GVRP with Capacitated AFS: G-VRP-CAFS

Bruglieri, Mancini, Pisacane, COR 2019: **Stations capacity may become a bottleneck**



Area in northern Italy: horizontal stretch of highway among Asti, Alessandria,Tortona

- η_s fueling pumps available for each station *s*

A more realistic variant of G-VRP!

Scenarios considered

Bruglieri, Mancini, Pisacane, COR 2019

- **With private AFSs:**
  - Always available to the transport company;
  - Avoiding queues taking into account AFSs capacity

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- **With private AFSs:**
  - Always available to the transport company;
  - Avoiding queues taking into account AFSs capacity
- **With public AFSs:**
  - Possibility of reserving in advance the use of their fueling pumps □ Multiple TWs associated with AFSs must be considered

Exact approaches for GVRP

Erdogan & Miller-Hooks, TRE 2012: 2-index MILP with AFSs clones to ensure each route be an elementary cycle

Koc & Karaoglan, Appl. Soft Comput. 2016: 3-index MILP without cloning AFSs; binary variables indicating if an AFV stops at an AFS traveling from a customer to another one

Leggieri & Haouari, TRE 2017: MILP + reduction procedure. Valid inequalities: 2-customer subtour elimination constraint. Preprocessing conditions: fixing some binary variables.

Andelmin & Bartolini, Transp. Sci. 2017: A set partitioning problem where columns are simple circuits on a multigraph.

Bruglieri, Mancini, Pisacane, TRC 2019: 2 MILP formulations without cloning AFSs. Dominance criteria to a-priori identify the more efficient AFSs. Valid inequalities.

Bruglieri et al., COR 2019: Path-based solution approach

Wang, Wang, Huang, TRB 2019. Branch&Price algorithm for heterogeneous GVRP

Koyuncu & Yavuz, TRE 2019. Duplicating nodes or arcs in green vehicle routing: A computational comparison of two formulations.

Heuristic approaches for GVRP

Schneider et al., Transp. Sci. 2014: Variable Neighborhood Search (VNS) & Tabu Search

Felipe et al., TRE 2014: Local search method for GVRP with multiple technology and partial recharges

Schneider et al., OR Spect. 2015: Adaptive VNS for VRP with Intermediate Stops.

Montoya et al., TRC 2016: Randomized route-first cluster second heuristic+ Set partitioning formulation

Affi, Derbel, Jarboui, Int. J. Ind. Eng. Comput. 2018: VNS for GVRP

Andelmin & Bartolini, COR 2019: A multi-start local search heuristic for GVRP based on a multigraph reformulation

Bruglieri et al., COR 2019: the exact path-based solution approach becomes a heuristic path-based approach for large sized instances

Capacitated Stations

Bruglieri, Mancini, Pisacane, Verolog 2017: MILP arc-based formulation and a repair heuristic

Froger et al., Cirrelt 2017: capacitated version of the E-VRP-NL; MILP formulations (able to solve only instances < 10 customers); Two-stage matheuristic

Keskin, Laporte, Çatay, COR 2019: limited fueling capacity in the E-VRPTW: MILP with time-dependent waiting times at stations for minimizing delays at customers due to possible queues at the stations

Bruglieri, Mancini, Pisacane, COR 2019: waiting times at the AFSs due to the queues are avoided through the fueling pump reservation.

Poonthalir & Nadarajan, ESWA 2019: GVRP in which each AFS is a M/M/1 queue. Chemical Reaction Optimization meta-heuristic.

GVRP-CAFS: notation

Set	Meaning
I	Set of customers
F	Set of AFSs
$N = I \cup F \cup \{0\}$	Set of nodes
$A = (i, j), \forall i, j \in N$	Set of arcs

Parameter	Meaning
0	Depot
m	Number of available AFVs
v	Average AFV speed
Q	Maximum fuel capacity for each AFV
r	Fuel consumption rate
$D_{\max}$	Distance an AFV can travel without refueling
$T_{\max}$	Maximum route duration
t_{ij}	Travel time to go from node i to node j
d_{ij}	Travel distance between node i and node j
p^{start}	Time spent for the initial refuel at the depot
p_s	Refueling time at AFS $s \in F$
p_i	Service time at customer $i \in I$
η_s	Number of fueling pumps at AFS $s \in F$

Bruglieri et al., COR2019: A-MILP

Additional sets

- Φ_s: ordered set of fueling pumps at AFS s
- $\Pi = \cup_{s \in F} \Phi_s$
- $\tilde{F}_h$: ordered set of clones of fueling pump h
- $\tilde{F}_h^{last} = \tilde{F}_h \backslash \{\text{last}(\tilde{F}_h)\}$
- $\hat{F} = \cup_{h \in \Pi} \; \tilde{F}_h$
- $\hat{N} = I \cup \hat{F} \cup \{0\}$
- $\Omega = \{i, j \in \hat{N}, i \neq j : d_{0i} + d_{ij} + d_{j0} \leq T_{max} v, d_{ij} \leq D_{max}, \nexists s \in F : i \in \tilde{F}_{h_1}, j \in \tilde{F}_{h_2}, h_1, h_2 \in \Phi_s\}$

Decision variables

- $x_{ij} = 1$ if AFV travels from *i* to *j* , 0 otherwise, $\forall (i,j) \in \Omega$,
- y_i = fuel level at node *i* , $\forall i \in \hat{N}$
- τ_i = arrival time at node *i* , $\forall i \in \hat{N}$

Bruglieri et al., COR2019: A path-based exact solution approach

- Each route is a combination of paths.
- Each path starts/ends from/to a node that can be either the depot or an AFS
- Each path that starts from the depot and ends to the depot is a route
- The number of paths is bounded by feasibility and dominance rules
- All the feasible non-dominated paths are given in input to the Set Partitioning like formulation (P-MILP) in order to determine the optimal set of routes
- P-MILP has been efficiently solved by cutting planes approaches (CP and CP-Proactive)

Our contribution: an Iterated Local Search approach

- Meta-heuristic framework (Lourenço et al. 2010) that iteratively applies local search, perturbation, and evaluation of the solution against an acceptance criterion;
- Local search performs the intensification phase;
- The perturbation and the acceptance criterion allow to explore the search space as well as to escape from local optima (diversification phase).

Cuervo et al., EJOR 2014: vehicle routing problem with backhauls

Silva et al., COR 2015: split delivery vehicle routing problem

Estrada-Moreno et al., ITOR 2019: multiperiod vehicle routing problem with price discounts for delivery flexibility

Iterated Local Search


```
Function ILS(inputs, parameters)
    baseSol ← createInitialSolutions(inputs, parameters)
    betsSol ← baseSol
    while stopping criterion not reached do
        newSol ← shake(baseSol)
        improving ← True
        while improving do
            newSol ← local-search(newSol)
            if cost(newSol) < cost(baseSol) then
                baseSol ← newSol
                if cost(newSol) < cost(bestSol) then
                    bestSol ← newSol
            else
                improving ← False
                if acceptance-criterion(baseSol) then
                    baseSol ← newSol

    return bestSol
```

Construction and perturbation phases

$\mathcal{R} \leftarrow \emptyset$;
while *stopping criterion not met* **do**
    Select an available AFV q;
    $R_q \leftarrow (0)$;
    while *a customer that can be visited exists* **do**
        randmoly select the next point i among the feasible ones;
        $R_q \leftarrow R_q \oplus (i)$;
    Select depot as final destination of q;
    $R_q \leftarrow R_q \oplus (0)$;
    $\mathcal{R} \leftarrow \mathcal{R} \cup \{R_q\}$;

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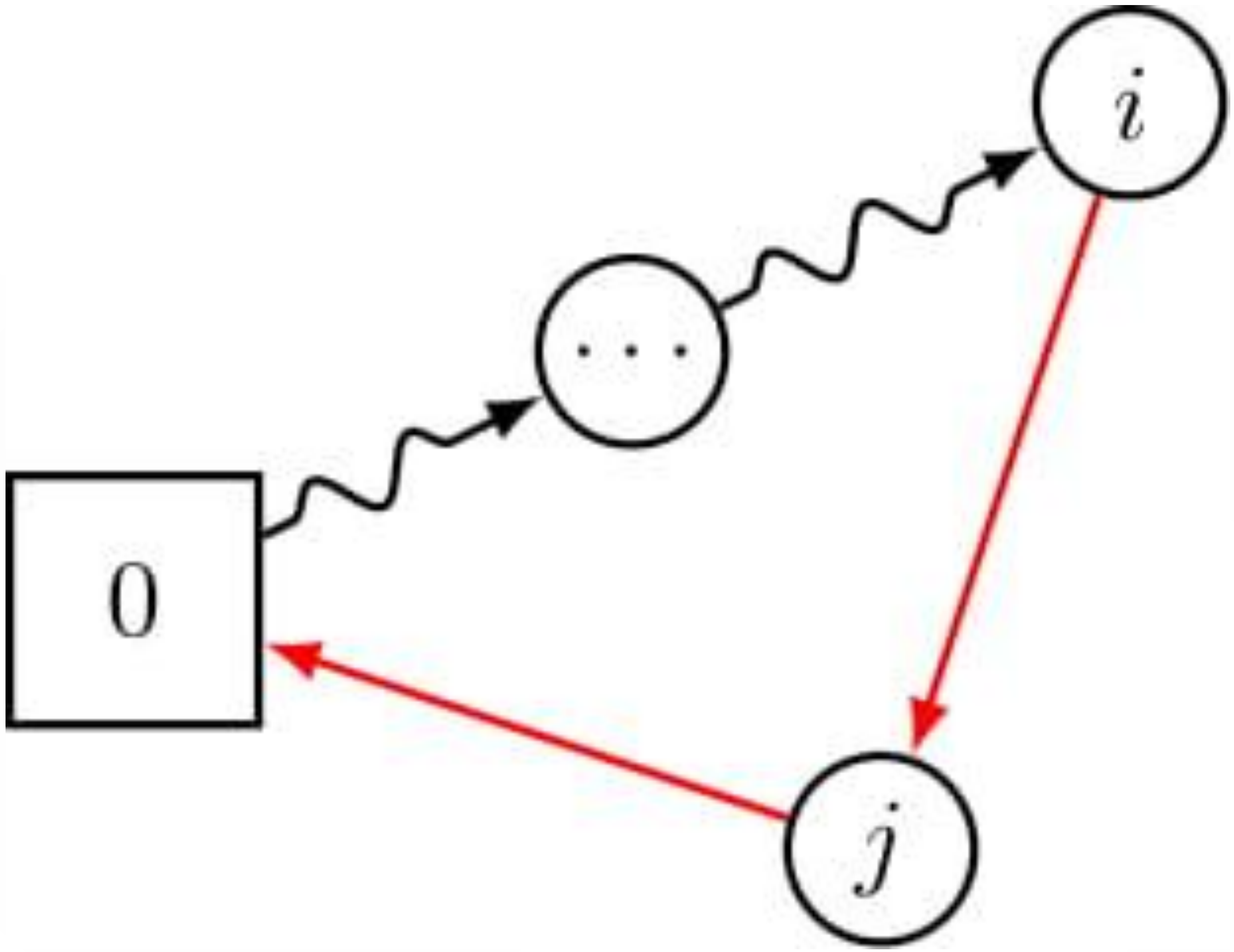
Perturbation: ruin and recreate

- Destroy a given percentage of the solution
- Re-construct the solution with the construction procedure

A customer that can be visited exists



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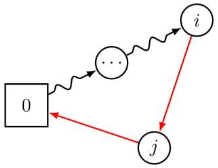

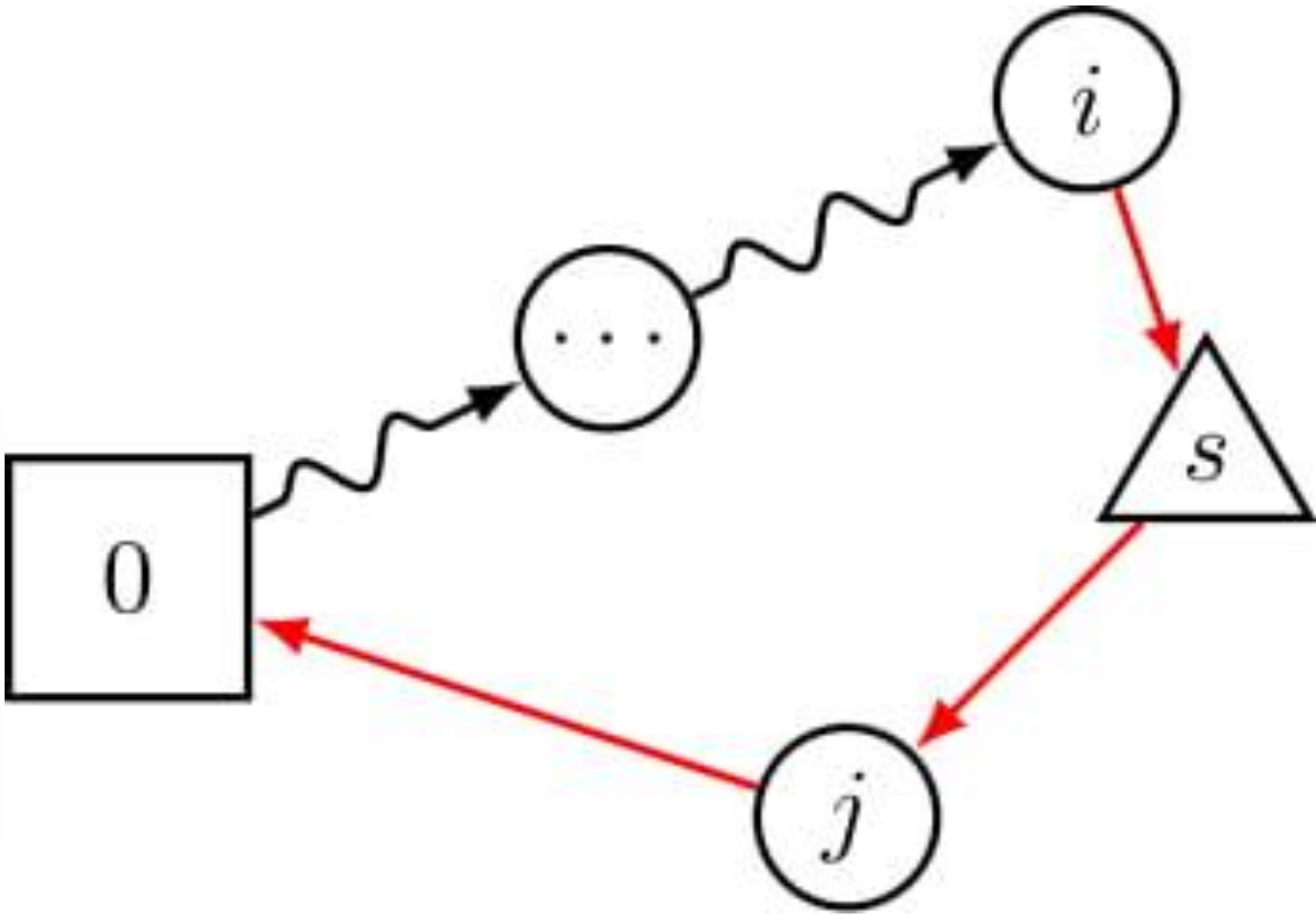

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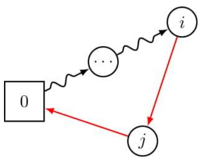
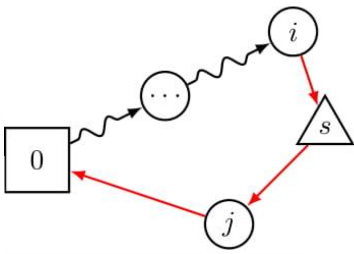
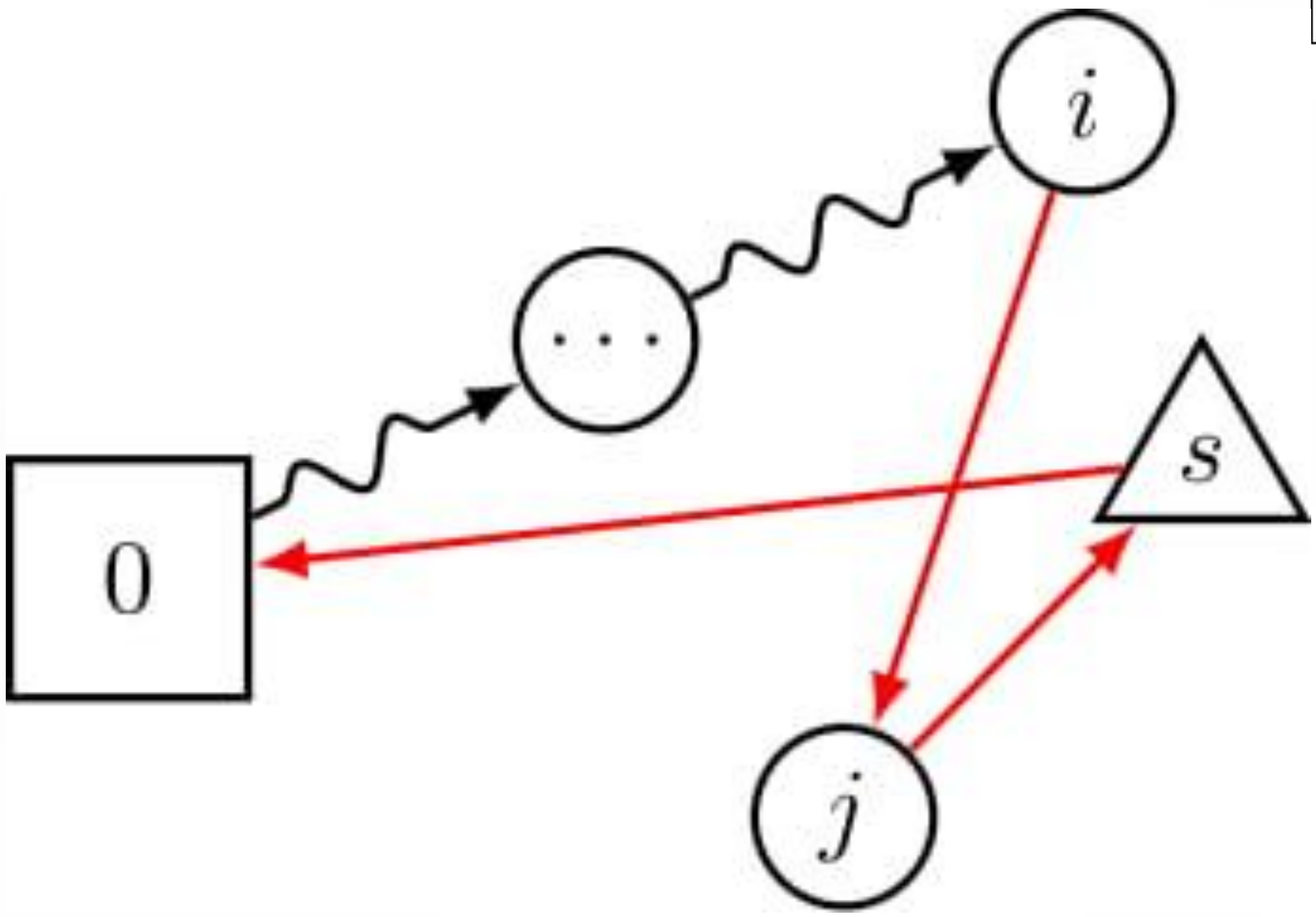
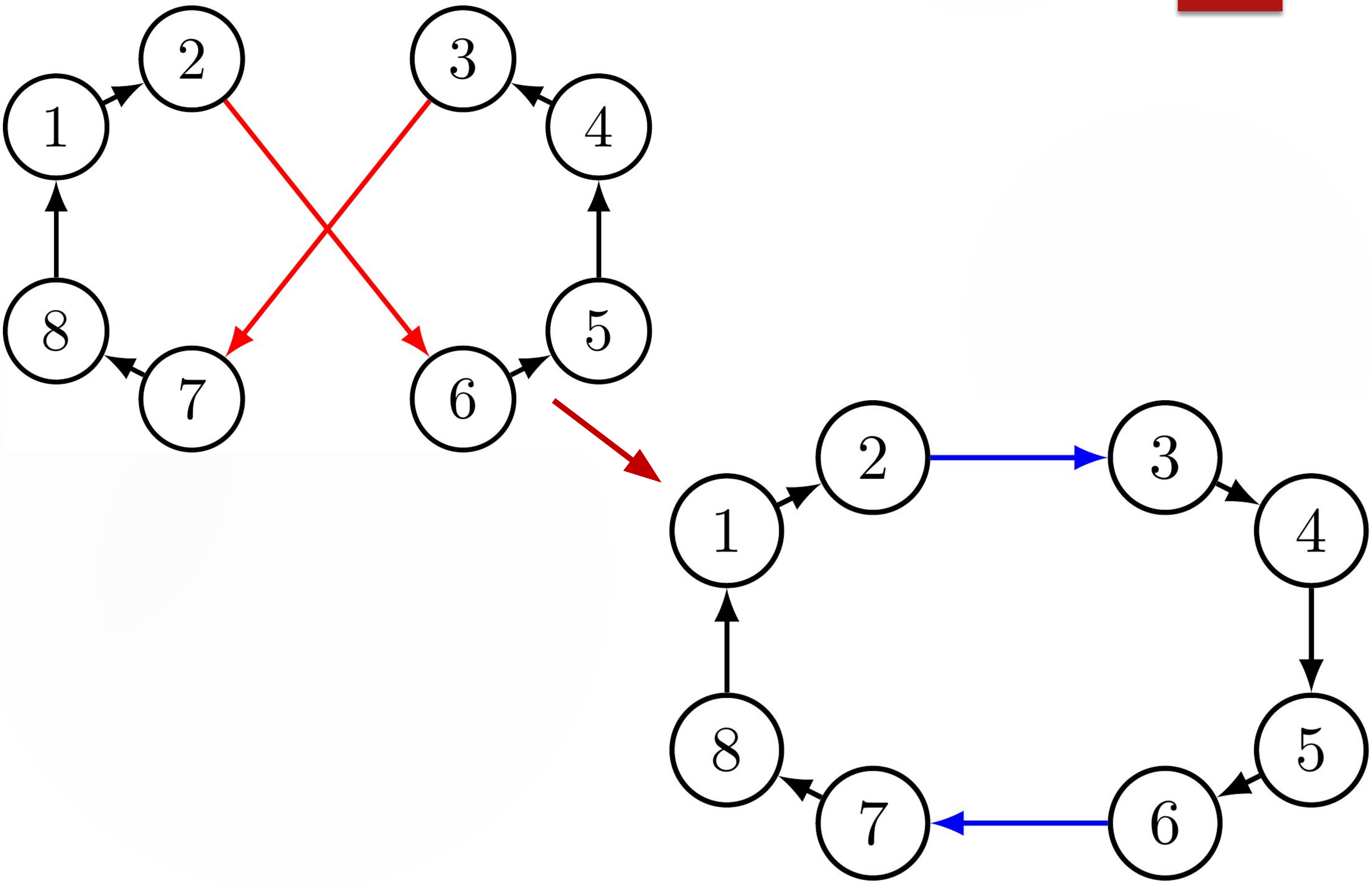


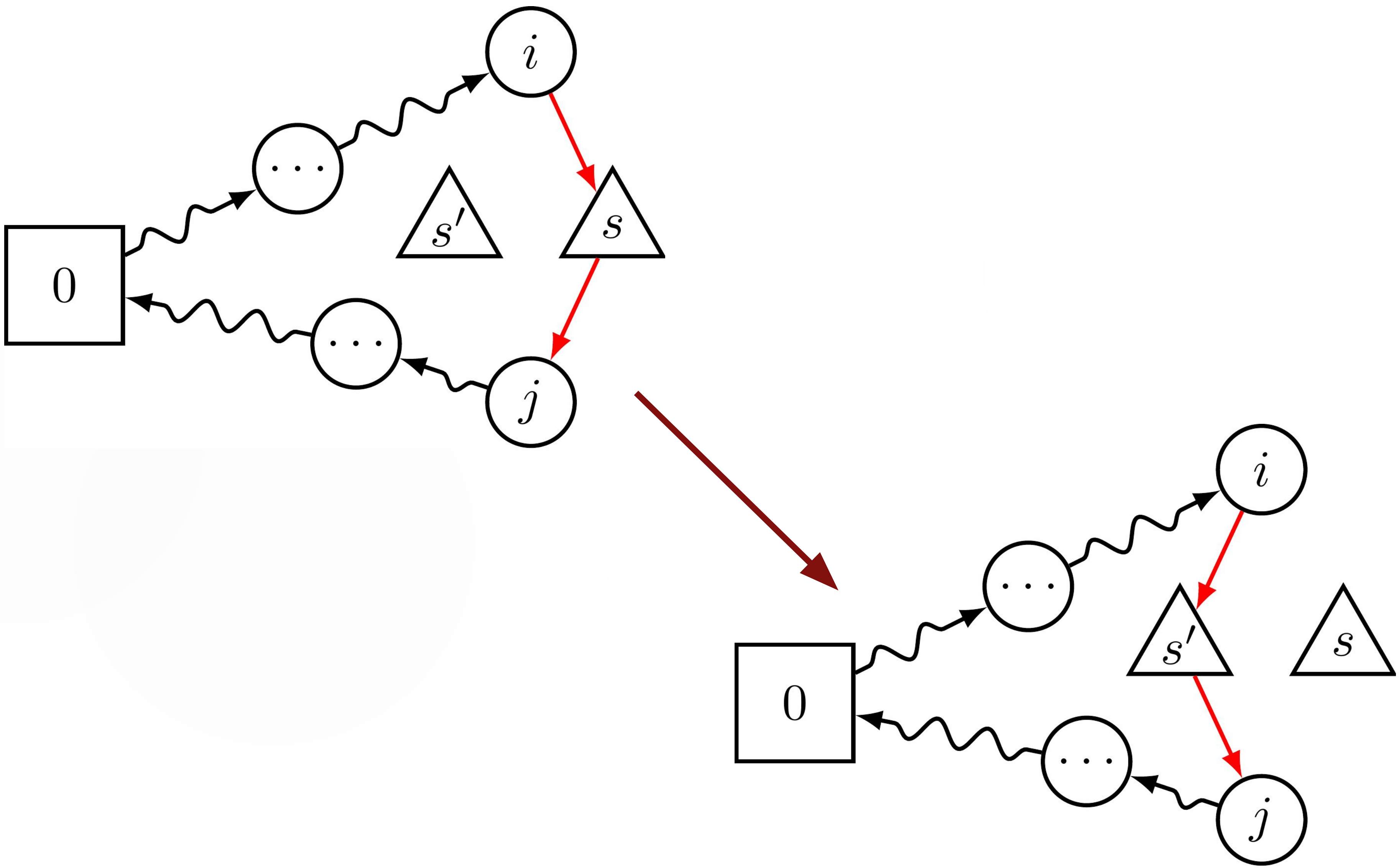




2-opt local search



Change AFS local search



Generating benchmark instances

From Bruglieri et al., COR 2019

- **TRIANGLE Set**: 10 instances
  - With 15 customers and 3 AFSs.
  - The AFSs lay in the middle between depot and customers.
  - **Medium challenging instances**.

- **CENTRAL set**: 10 instances
  - With 15 customers and 1 AFS at the center of customers area.
  - Depot far from customers.
  - **Extremely challenging instances.**

Numerical results: TRIANGLE set

	CP-Proactive		ILS			
	Distance (1)	CPU (2)	Distance (3)	CPU (4)	%-gap (3-1)	Ratio (4/2)
Triangle1	1871.61	1.04	1871.61	1.80	0.00	1.73
Triangle2	2191.73	4.09	2258.48	1.94	3.05	0.47
Triangle3	1872.12	4.56	1872.12	2.12	0.00	0.46
Triangle4	1869.07	4.52	1963.83	1.80	5.07	0.40
Triangle5	1852.73	11.02	1972.42	2.03	6.46	0.18
Triangle6	1865.49	5.25	1876.49	1.87	0.59	0.36
Triangle7	1898.00	3.10	1922.16	1.88	1.27	0.61
Triangle8	2197.49	13.76	2321.31	2.04	5.63	0.15
Triangle9	1862.50	6.30	2005.62	1.90	7.68	0.30
Triangle10	1864.73	5.04	1975.26	1.97	5.93	0.39
Average	1934.55	5.87	2003.93	1.94	3.57	0.51

Numerical results: CENTRAL set

	CP-Proactive		ILS			
	Distance (1)	CPU (2)	Distance (3)	CPU (4)	%-gap (3-1)	Ratio (4/2)
Central1	953.94	130.61	1481.86	10.15	55.34	0.08
Central2	948.69	441.91	1494.38	2.08	57.52	0.00
Central3	943.12	3600.00	1614.76	5.25	71.21	0.00
Central4	967.96	3600.00	1837.30	0.70	89.81	0.00
Central5	714.55	2.98	1201.34	5.99	68.12	2.01
Central6	844.43	1348.23	1026.25	0.86	21.53	0.00
Central7	862.68	148.07	1064.40	2.39	23.38	0.02
Central8	712.83	4.60	1030.28	3.84	44.53	0.83
Central9	866.39	22.10	1053.70	1.41	21.62	0.06
Central10	901.19	453.02	1244.13	9.13	38.05	0.02
Average	871.58	975.15	1304.84	4.18	49.11	0.30

Conclusions

- ILS: promising results in very short computational times
- the possibility to solve large sized instances in reasonable computational times

Future Developments

- Improve the method to obtain higher quality solutions
  - Additional local search moves, Path relinking, hybridization, ...
- Extend the ILS to address also the private scenario

Thank you for your attention!

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