AUSTRIAN INSTITUTE OF TECHNOLOGY
TOMORROW TODAY

On-demand automated guided vehicles in yard logistics

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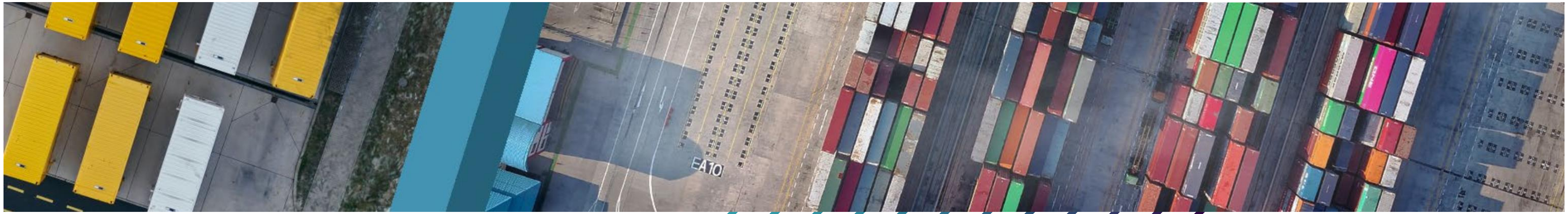
AWARD
Scaling autonomous logistics



AWARD

H2020 Project

- **A**ll **W**eather **A**utonomous **R**eal logistics operations and **D**emonstrations
- Efficient and safe connected and automated heavy-duty vehicles in real logistics operations
- Potential to address key issues in commercial transportation:
  - Lack of qualified drivers in Europe
  - Number of accidents with trucks unacceptably high (due to driver failures)
  - Utilization of freight transport capacity is below 50%

AWARD has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement No 101006817

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Scaling autonomous logistics

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H2020 Project

- Driving autonomously **on all roads at all speeds** with all sorts of **known and unknown** hazards certainly is and will be a challenge

- Developing and operating **safe autonomous transportation systems**
  - In a wide range of real-life logistic use cases in a variety of different scenarios.
  - Solution will be based on multiple sensor modalities and an embedded teleoperation system **to address 24/7 availability**
  - Vehicles will be deployed, integrated and operated in a **variety of real-life use cases** to validate their value

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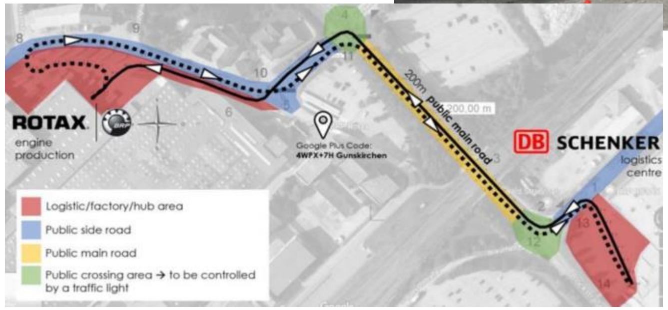
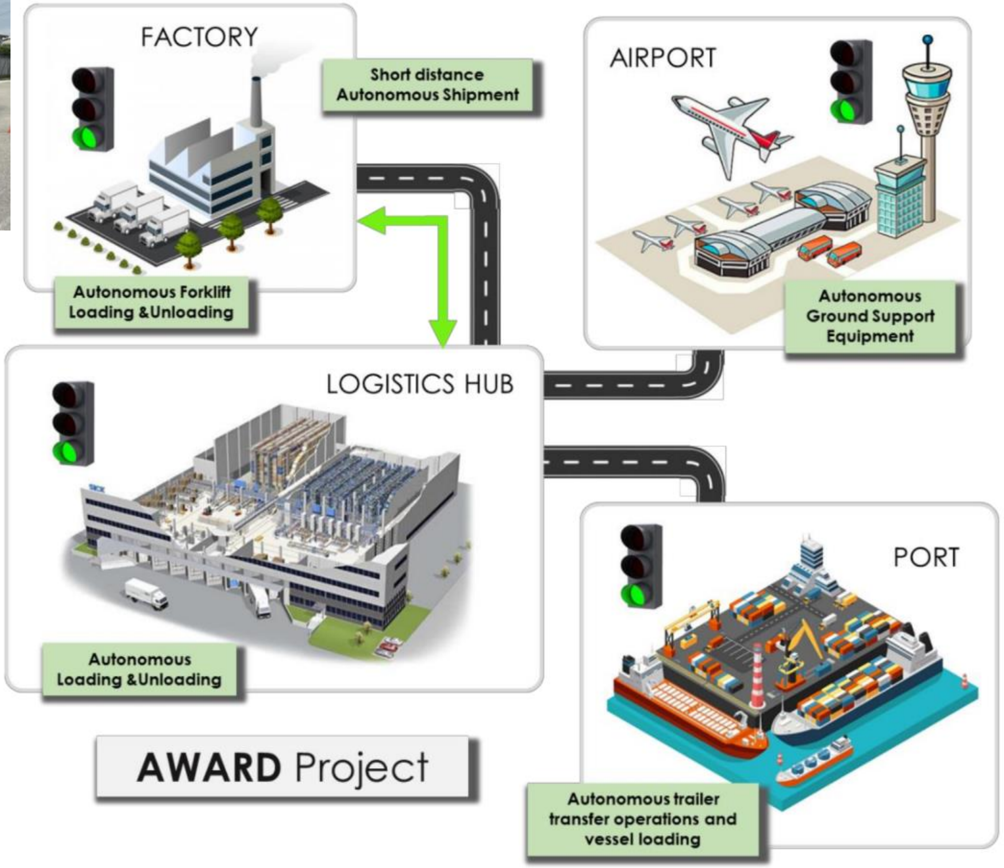
4 Use Cases in Europe





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Consortium

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Scaling autonomous logistics

Sensors	Autonomous Driving System	Heavy-Duty Vehicles manufacturer	Fleet Management & Supervision	End-users Industrial sites
Continental The Future in Motion	EASY MILE	KAMAG	APPLIED AUTONOMY	DFDS
NAVTECH RADAR	Continental The Future in Motion	KION GROUP	DFDS	AVINOR
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Certification and proving grounds

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Impact assessment, business modelling and regulatory frameworks

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Agenda

- **Fleet Management**
  - Generate a schedule for vehicles
  - Consider different weather and road conditions
  - Non-blocking vehicles

- Time-dependent Shortest Path Problem
- Time-dependent Pickup and Delivery Problem with Time Window
- Conflict-free Large Neighboorhood Search

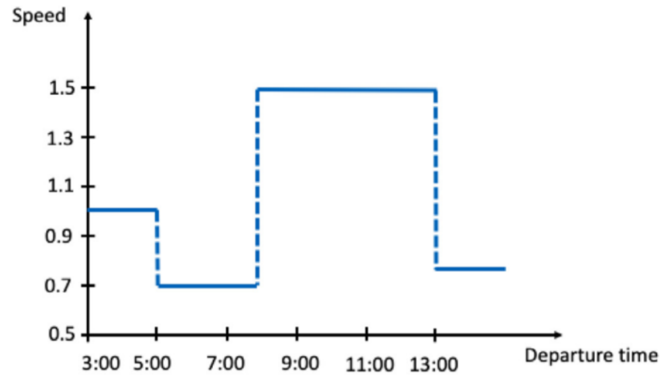
PROBLEM DESCRIPTION

Time-dependent road network

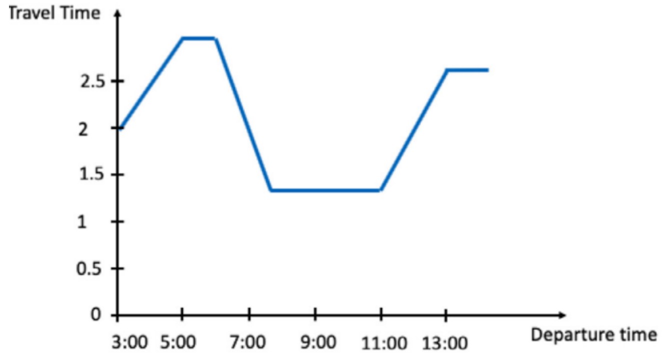
- Road network is a directed graph $G = (V, A)$
  - Set of vertices $V = \{0, \dots, n\}$
  - Set of arcs A, road segments between a pair of vertices

- Each arc $(i, j) \in A$ is associated with a
  - Distance d_{ij}
  - Time-dependent speed function $\mathrm{v_{ij}}$: $t \rightarrow R^+$
  - Time-dependent cost function: $c_{ij}: t \rightarrow R^+$ (= travel time)

- Each speed function is a stepwise function from which a piecewise travel time function can be derived



(a) Speed function



(b) Travel time function

(Gmira et al., EJOR 2021)

PROBLEM DESCRIPTION

Time-dependent Pickup and Delivery Problem with Time Windows

- Set of n requests r each with:
  - Pickup and delivery node pair $\{i, n+i\} \in V$
  - Demand for pickup q_{i+} and delivery q_{i-}
  - Service time for pickup s_{i+} and delivery s_{i-}
  - Time window $tw_r = [a_i, b_i]$ (either at pickup or delivery, soft)

- Set of m vehicles K starting at parking positions $z_k \in V$ with capacity C_k

- TDPDPTW is to generate routes for all vehicles:
  - Feasibility: Conflict-free, time windows, capacity constraint
  - Objective: Maximize the number of served requests
    Minimize the total lateness and travel time of the routes

SOLUTION APPROACH I

Time-dependent Dijkstra‘s algorithm with new weighting function

- Time-dependent variant of Dijkstra‘s algorithm
  - Minimum cost path between a source and destination node at a departure time t
  - Forward: travel time for departure time t at source
  - Backward: travel time for arrival time t at destination

- Situations defined by operators
  - Time period with a start and an end time $p = [a_p, b_p]$
  - Speed defined over this interval $v_{ij}^{+}(p)$: $v_{ij}(t)$ for all $t \in [a_p, b_p]$
  - Consider special case when situation is “road closed“
    - Either waiting until b_p or detour

SOLUTION APPROACH I

Time-dependent Dijkstra with new weighting function

- Award weighting function
  - Extension of procedure in Ichoua et al., 2003
  - From current node to successor through arc (i, j) at time t
  - Special case road closed
    - No distance covered when waiting

Algorithm 1: Travel costs to a successor of a node.

Input : arc (i, j), arrival time t, $p = 0$

Output: costs c_{ij}

while $t \geq a_p$ **do**

  $p = p + 1$

$c' = b_p - t$

$d' = c_{ij} = 0$

$d = c' \cdot v^+_{ij}(p)$ //if $v^+_{ij}(p)$ is road closed $\rightarrow d = 0$

while $d \leq d_{ij}$ **do**

  $c_{ij} = c_{ij} + c'$

  $p = p + 1$

  $d' = d$ //if $v^+_{ij}(p)$ is road closed $\rightarrow d' = 0$

  $c' = b_p - a_p$

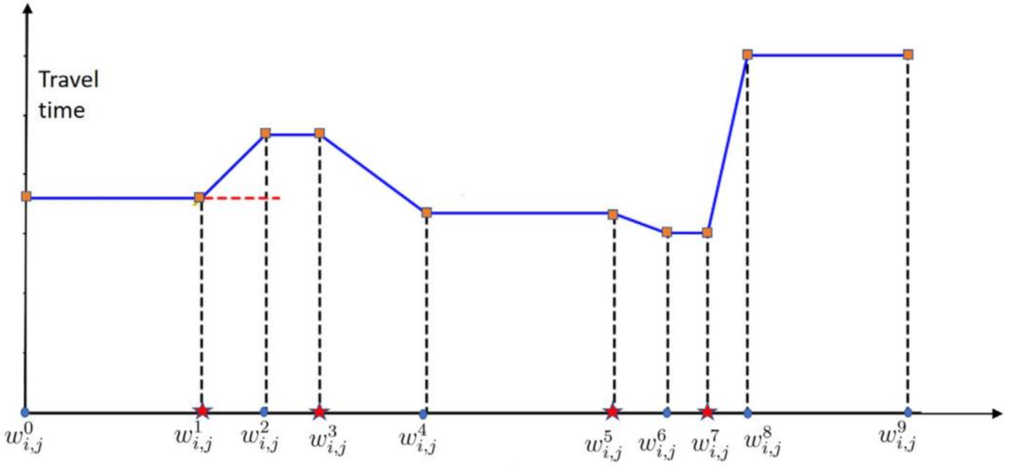
  $d = d' + (c' \cdots v^+_{ij}(p))$

return $c_{ij} + ((d_{ij} - d')/v^+_{ij}(p))$

SOLUTION APPROACH II

Time-dependent distance matrix

- Efficiently store travel times between two nodes for a given time
  - Entry for every possible departure → high time resolution (ms)
- Changes in travel time depend on given situations (periods)
  - Calculate the times when the speed changes on arc (ij)
    → Set of breakpoints for arc (ij): $W_{(ij)} = \{w^0_{(ij),}\dots, w^c_{(ij)}\}$
- Entry in matrix for not changing travel times
  - Travel cost $c_{ij}^{w^0_{(ij)},w^1_{(ij)}}$ between i and j
    for all time points $t \in [w^0_{(ij)}, w^1_{(ij)}]$
- Travel costs of other instants stored in cache



(Pan et al., COR 2021)

SOLUTION APPROACH II

Compute time-dependent distance matrix

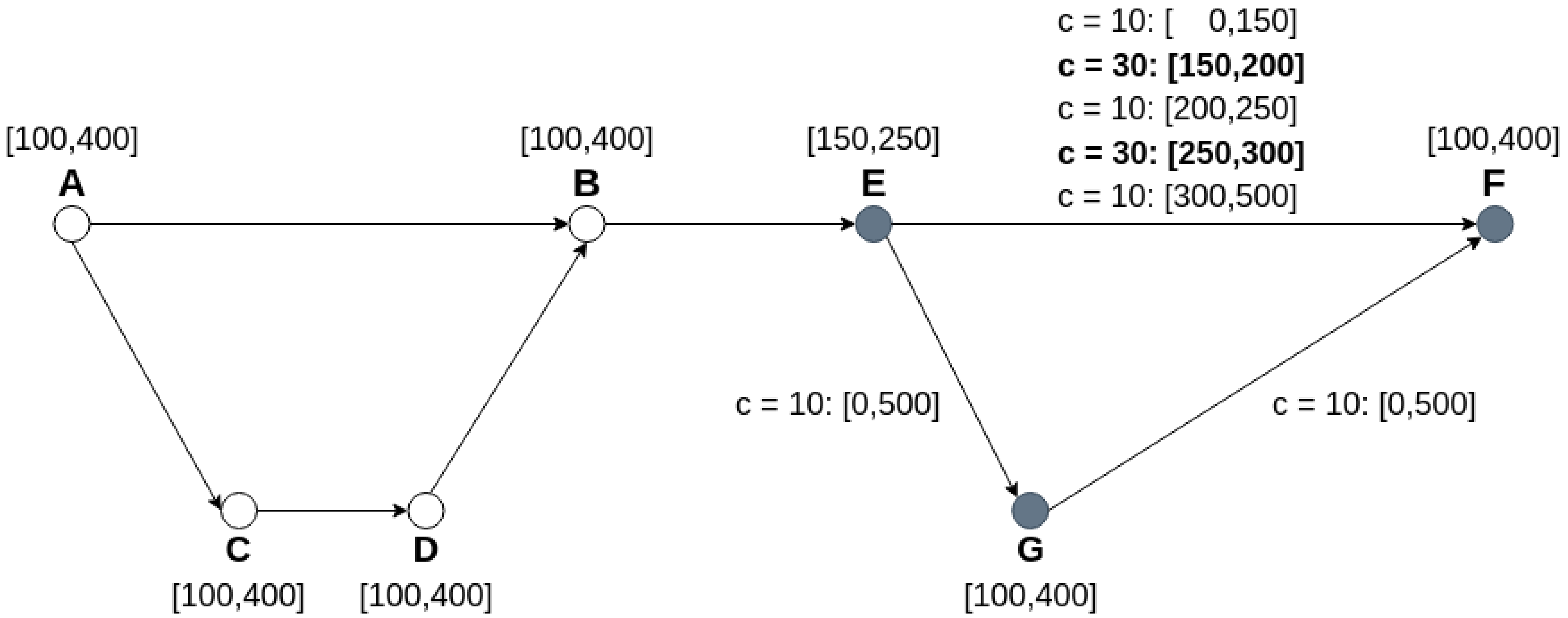
- Calculation of distance matrix entry between node x and node y
  - Determine all departure times $e \in E$ in x and their resulting paths p_{xy}^{e+} (increasing)
  - If there is no change (travel cost <u>and</u> path) $\rightarrow$ entry to matrix

- Determine all departure times $e \in E$ in x:
  - Compute set of paths P with arrival in y at a_y and b_y (backward Dijkstra)
  - For all arcs (i, j) on the paths plus for all incoming arcs $(i', j), i' \neq i$
    $\rightarrow$ compute set of breakpoints $W_{(ij)}$
  - For all breakpoints calculate departure in x and path from x to i, i' respectively
    - Departure e in x: backward Dijkstra with arrival in i at $w_{(ij)}^{c}$
    - Calculate path from x to i at departure e with forward Dijkstra

SOLUTION APPROACH II

Time-dependent distance matrix

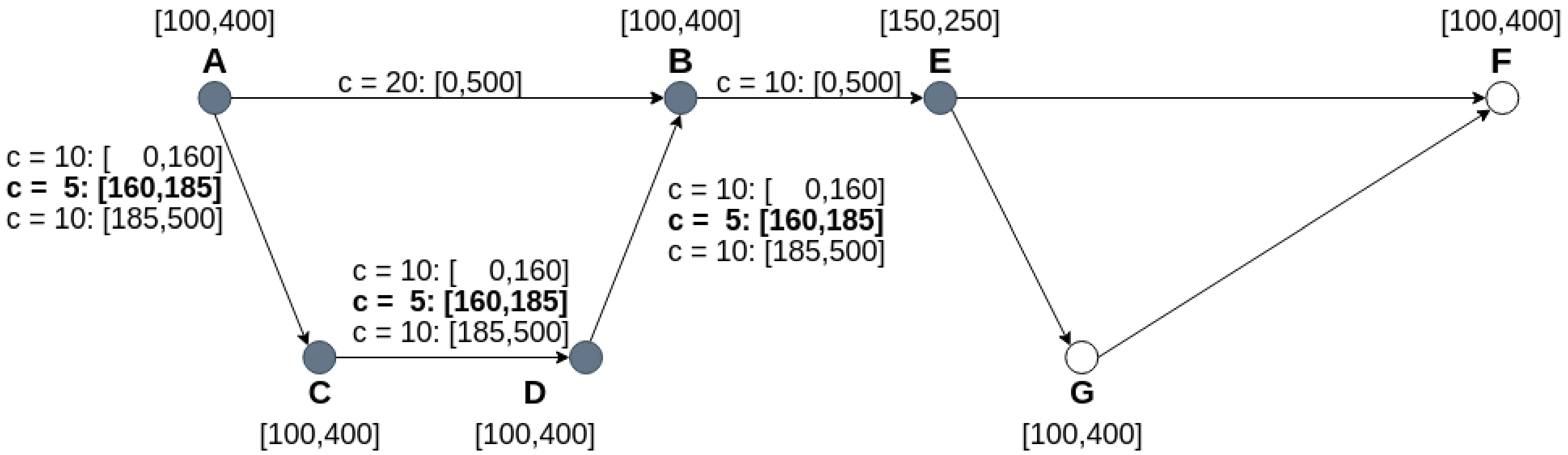
- Calculate matrix entry for **route from node E to node F**
  - Departure at 140 → path is EF with costs 10
  - Departure at 150 → path is EG.GF with costs 20 (detour)



SOLUTION APPROACH II

Time-dependent distance matrix

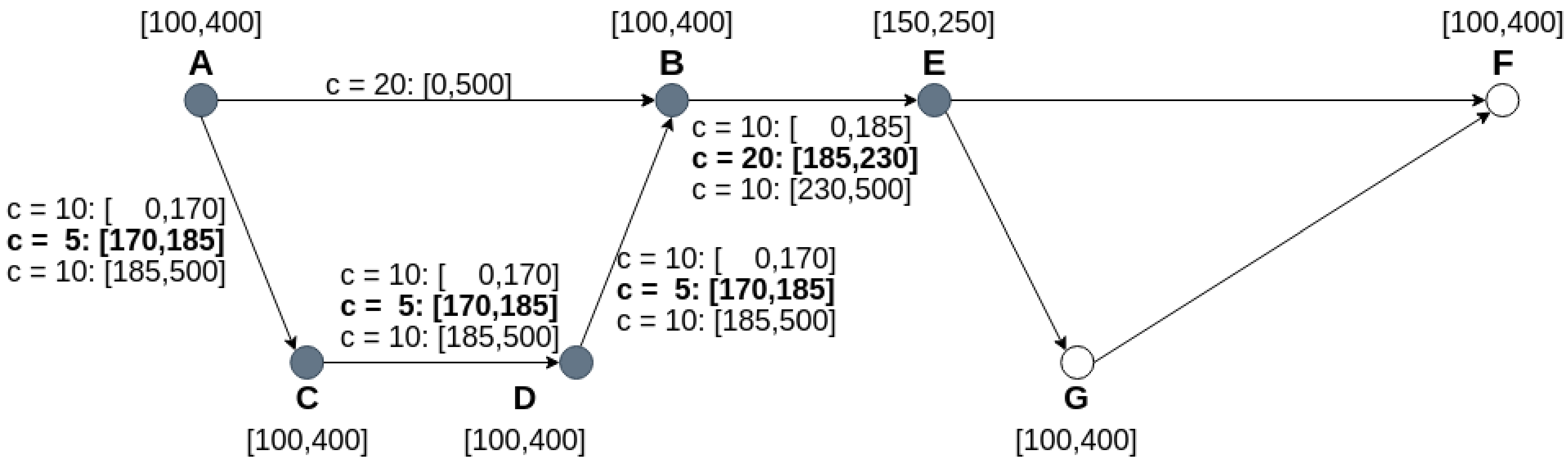
- Calculate matrix entry for **route from node A to node E**
  - Example that considering incoming arcs is necessary:
    - Departure at 120 and 220 → path is AB-BE with costs 30 (**no situations on path!**)
    - Departure at 160 → path is AC-CD-DB-BE with costs 25 (detour)



SOLUTION APPROACH II

Time-dependent distance matrix

- Calculate matrix entry for **route from node A to node E**
  - Example that considering path not only departure in A is necessary:
    - Departure at 160 → path is AB-BE with costs 35
    - Departure at 170 → path is AC-CD-DB-BE with costs 35 (**same costs put different path!**)



SOLUTION APPROACH III

TW Calculator TDPDPTW (soft)

- Improvement method to calculate time windows for the VRPTW
- Introduced by Vidal et al., 2013
- Efficiently calculate penalties according to time window constraints
  - Forward and backward
  - Concatenation

Algorithm 1 : calculateTimeWindowFeasibility(Sequence σ)

$i = first(\sigma);\ TW = 0;\ E = e_0;\ L = l_0;\ D = s_0;$
for $\forall j$ in $\sigma \setminus 0$ **do**
  $\Delta = D - TW + t_{ij};$
  $\Delta^{WT} = max\{0,\ e_j - \Delta - L\};$
  $\Delta^{TW} = max\{0,\ E + \Delta - l_j\};$
  $D = D + s_j + \Delta^{WT} + t_{i,j};$
  $TW = TW + \Delta^{TW};$
  $E = max\{e_j - \Delta, E\} - \Delta^{WT};$
  $L = min\{l_j - \Delta, L\} + \Delta^{TW};$
  $i = j;$
end for

SOLUTION APPROACH III

TW Calculator TDPDPTW (soft)

- Adapt the sequence-based TW calculation from Vidal
- Store values (duration, lateness) for earliest (E) **and** latest departure (L)
- Calculate departure times for E and L
  - When $E = L \longrightarrow$ use forward extension of Vidal
  - Otherwise, if E and/or L changes:
    - Update values and check if there are changes in travel costs
    - Worst case: Update until the beginning of the sequence
- Determine best departure in depot for the node sequence

SOLUTION APPROACH IV

Conflict-free Large Neighborhood Search (LNS)

- (Adaptive) Large Neighborhood Search as in Ropke and Pisinger, 2006
  - Remove requests from solution (up to 60%) and insert them again
    - Destroy operators: Random and Worst
    - Repair operators: Greedy Repair, Regret Repair

- Only conflict-free solutions are allowed
  - Conflict: if vehicles blocks another vehicle at a stop
  - Whenever feasibility of solution is calculated:
    - Check for each vehicle route if it passes a stop where another vehicle stays
      → Solution is infeasible

PRELIMINARY RESULTS

Time-dependent PDPTW with no conflicts

- Instances on road network generated by an operator
  - Road network consists of 173 nodes and 252 edges
  - 30, 40, 50 customer requests, 5 or 10 situations, and 3 vehicles
- First results show benefit of implementing a time-deent distance matrix
  - Percentage of runtime for travel time calculation to total runtime

# requests	5 situations		10 situations	
	No matrix	Matrix	No matrix	Matrix
30	3.08	1.67	3.61	1.46
40	2.34	1.01	2.66	0.79
50	4.20	2.01	4.09	1.34

PRELIMINARY RESULTS

Time-dependent PDPTW with no conflicts

- Efficient time window calculation with time-dependent travel times
  - Implemented and tested for forward method (many possibilities)

    → Extension to backward calculation (allowing concatention in constant time)

    → Compare to other time window calculations

- Conflict-free vehicle routes are generated for all instances
  - Dealing with larger instances (more vehicles):

    → Operator: Relocate vehicle to parking position

THANK YOU!

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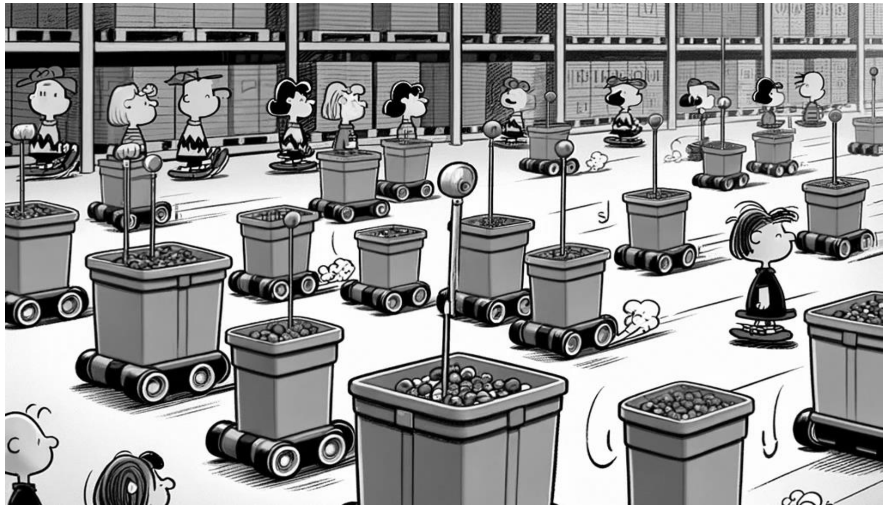

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