

# Anticipatory Freight Scheduling in Sychromodal Transport



Arturo E. Pérez Rivera

# ¡Gracias!

**Thank you**

Bedankt

Dankie

Danke

Dziękuję Ci

хвала

谢谢

धन्यवाद

Obrigado

Grazie

*Merci*

Mulțumesc

Teşekkür ederim

Terima kasih

متشکرم

شکرا

# Anticipatory Freight Scheduling in Sychromodal Transport

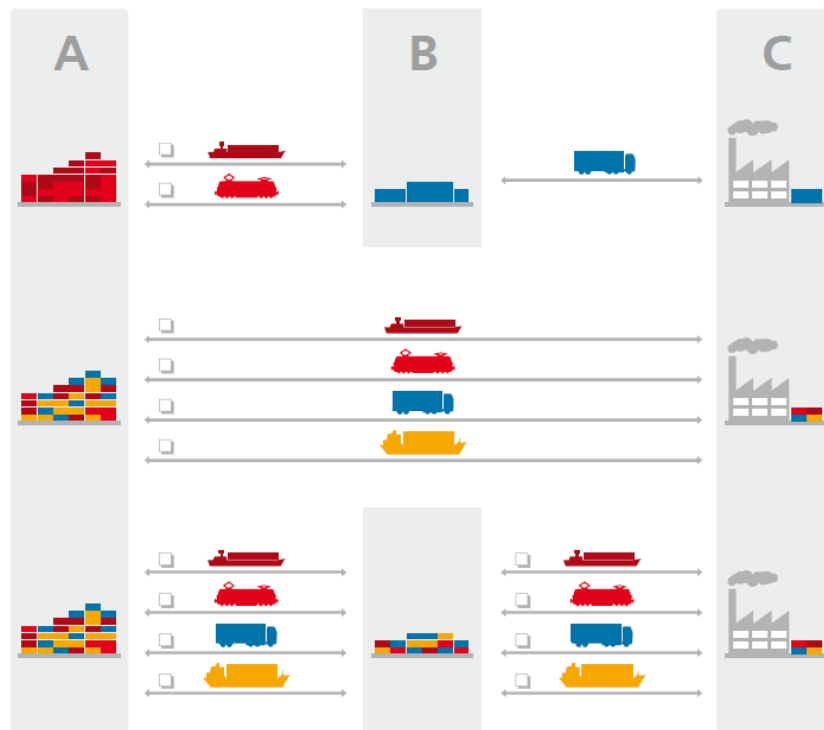


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# WHAT IS SYNCHROMODAL TRANSPORT?

MULTI-MODAL FREIGHT TRANSPORT WITH FLEXIBILITY IN *MODE*, *PATH*, AND *TIME*



The flexibility of synchronomodal transport:

1. *Provides new consolidation opportunities*
2. *Requires a network-wide and multi-period view on performance*

\*Source of artwork: European Container Terminals (ECT) – The future of freight transport (2011).

# WHAT IS ANTICIPATORY SCHEDULING?

SCHEDULING TODAY THINKING ABOUT WHAT HAPPENS TOMORROW

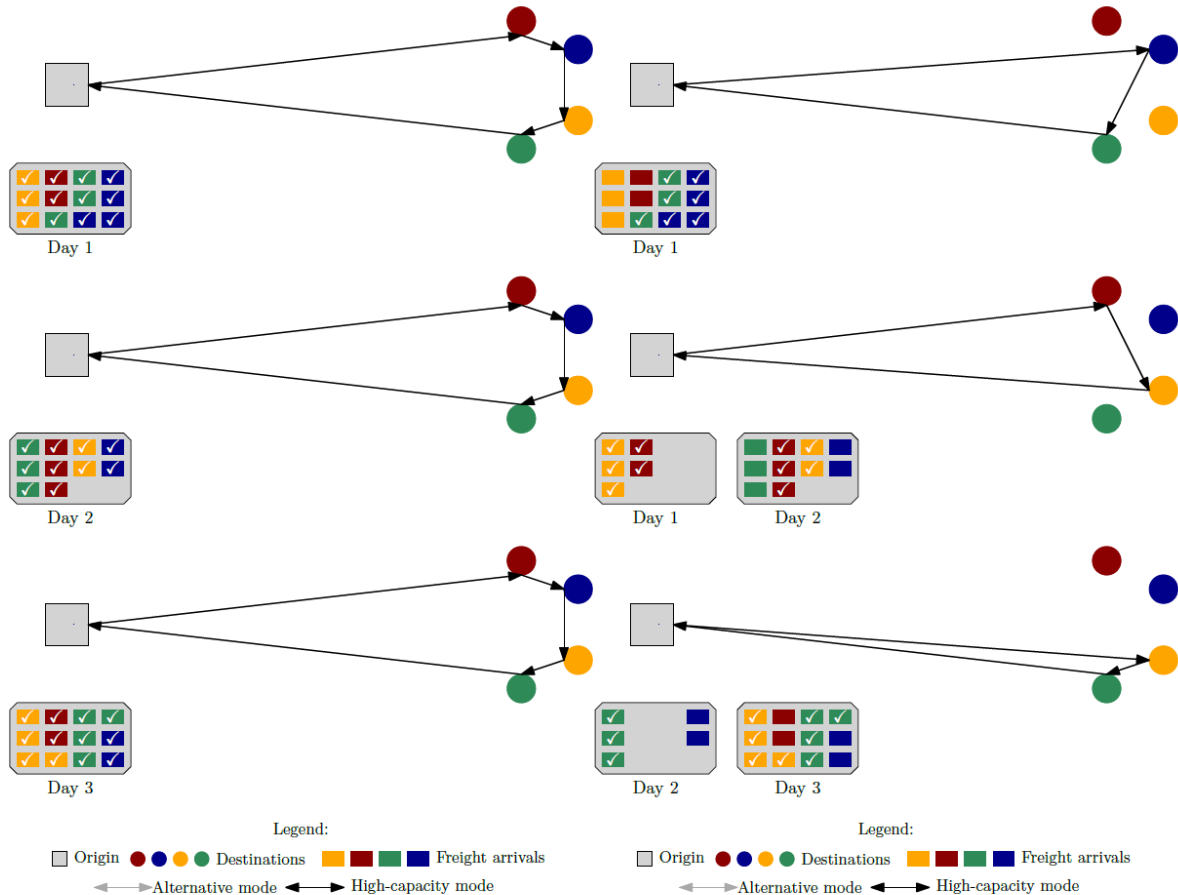
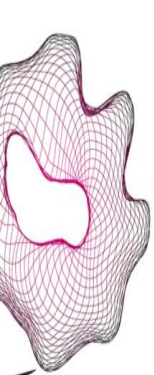


Figure 1.2: Example of a myopic schedule    Figure 1.3: Example of an anticipatory schedule



# HOW DO WE STUDY ANTICIPATORY SCHEDULING?

## SUB-FIELD OF APPLIED MATHEMATICS CALLED OPERATIONS RESEARCH (O.R.)

### 2.3. Mathematical Model 25

$$0 \leq x_{i,d,k}^C \leq C_{i,d,0,k} \forall d \in \mathcal{D}, k \in \mathcal{K} \quad (2.2c)$$

$$\sum_{d \in \mathcal{D}} \sum_{k \in \mathcal{K}} x_{i,d,k}^H \leq Q_i \quad (2.2d)$$

$$\sum_{d \in \mathcal{D}} \sum_{k \in \mathcal{K}} x_{i,d,k}^C \leq Q_i \quad (2.2e)$$

$$x_{i,d,k}^H, x_{i,d,k}^C \in \mathbb{Z}^+ \cup \{0\} \quad (2.2f)$$

The costs of a decision depend on the destinations visited with the high-capacity mode and the use of the alternative mode. We define  $y_{i,d,t} \in \{0,1\}$  as the binary variable that gets a value of 1 if destination  $d$  is visited by the high-capacity mode at stage  $t$  and 0 otherwise. We define  $z_{i,d}$  as the variable representing the number of freights to and from destination  $d$  that were transported with the alternative mode. These variables depend on the state and decision variables, as seen in (2.3b) and (2.3c). Using these variables, the costs at stage  $t$  can be defined as a function of  $x_t$  and  $S_t$ , as shown in (2.3).

$$C(S_t, x_t) = \sum_{D \subseteq \mathcal{D}} \left( C_D \cdot \prod_{d' \in D} y_{i,d',t} \cdot \prod_{d' \in \mathcal{D} \setminus D} (1 - y_{i,d',t}) \right) \quad (2.3a)$$

The goal is to perform all jobs, within their time-window, while minimizing routing and terminal assignment costs. To model the routing costs, we introduce (i) a fixed cost  $C_k^F$  for using truck  $k \in \mathcal{K}$  and (ii) a variable cost  $C_{i,j,k}^R$  for its movement over arc  $(i,j) \in \mathcal{A}$ . To model the terminal assignment costs, we introduce a cost  $C_{i,j}^T$  for assigning terminal  $d \in \mathcal{V}^D$  to job  $r \in \mathcal{V}^C$ . Using the parameters and variables above, the optimization goal can be achieved solving the mathematical program shown in (5.1).

The objective is of (2.3) over all  $t \in$  horizon, and thus expected costs over and we do not know objective has to be as a function that is to find the policy given an initial sta

Using Bellman's of recursive equation

$$\min_x \sum_{k \in \mathcal{K}} \left( C_k^F \cdot \sum_{j \in \delta^+(i)} x_{j,i,k} \right) + \sum_{k \in \mathcal{K}, (i,j) \in \mathcal{A}} C_{i,j,k}^R x_{i,j,k} \quad (5.1a)$$

$$+ \sum_{k \in \mathcal{K}, r \in \mathcal{V}^C, d \in \delta^+(r), j \in \mathcal{V}^D} C_{i,j}^T x_{r,d,k} \quad (5.1b)$$

$$\sum_{k \in \mathcal{K}, (i,j) \in \delta^+(r)} x_{j,i,k} = 1, \forall r \in \mathcal{V}^D, \delta^+(r) \neq \emptyset \quad (5.1c)$$

$$\sum_{k \in \mathcal{K}, (i,j) \in \delta^+(r)} x_{j,i,k} = 1, \forall r \in \mathcal{V}^C, \delta^+(r) \neq \emptyset \quad (5.1d)$$

$$(1 - D_r) \left( \sum_{j \in \delta^+(r)} x_{j,i,k} - \sum_{j \in \delta^-(r)} x_{i,j,k} \right) = 0 \quad (5.1e)$$

$$\forall r \in \mathcal{V}^D, \delta^+(r) \neq \emptyset \text{ and } \delta^-(r) \neq \emptyset, k \in \mathcal{K}(r) \quad (5.1f)$$

$$\sum_{k \in \mathcal{K}, j \in \delta^-(r)} x_{r,i,k} = 1, \forall r \in \mathcal{V}^D \quad (5.1g)$$

$$\sum_{k \in \mathcal{K}, j \in \delta^-(r)} x_{d,i,k} \leq 1, \forall d \in \mathcal{V}^D \quad (5.1h)$$

$$\sum_{j \in \delta^+(i)} x_{i,j,k} - \sum_{j \in \delta^-(i)} x_{j,i,k} = 0, \forall i \in \mathcal{V}^C \cup \mathcal{V}^D, k \in \mathcal{K} \quad (5.1i)$$

$$E_i \leq w_i, \forall i \in \mathcal{V} \quad (5.1j)$$

$$\sum_{k \in \mathcal{K}} [x_{i,k} (w_i + S_i + T_{i,j} - w_j)] \leq 0, \forall i, j \in \mathcal{V} \quad (5.1k)$$

$$\sum_{k \in \mathcal{K}} [x_{i,k} (w_i + S_i + T_{i,j} - T_{j,i}^D)] \leq 0, \forall i \in \delta^-(F_k), k \in \mathcal{K} \quad (5.1l)$$

$$x_{i,j,k} = 0, \forall k \in \mathcal{K}, j \in \delta^-(r) \setminus \{i\} \quad (5.1m)$$

### 2.4 Solution Algorithm

We propose a solution algorithm based on Approximate Dynamic Programming (ADP). ADP is a framework that contains several methods for tackling the curses of dimensionality in an MDP. The general idea of ADP is to modify Bellman's equations with a series of components and algorithmic manipulations in order to approximate their solution, and thus the optimal policy. In this section, we elaborate on the components and algorithmic manipulations we use, as shown in Algorithm 1. First, we introduce the concepts of *post-decision state* and *forward dynamic programming*, which tackle the first- and third-dimensionality issue mentioned in Section 2.3.3. Second, we introduce the concept of *basis functions* as an approximation of the value of the post-decision states. Finally, we describe a way of tackling the second dimensionality issue of finding the optimal decision for a single stage.

#### Algorithm 1 ADP Solution Algorithm

```

1: Initialize  $V_i^0, \forall i \in \mathcal{T}$ 
2:  $n := 1$ 
3: while  $n \leq N$  do
4:    $S_i^0 := S_i$ 
5:   for  $t = 0$  to  $T^{\max} - 1$  do
6:      $\hat{V}_i^t := \min_{x_t} (C(S_i^t, x_t^0) + V_i^{t-1}(S^{M,x}(S_i^t, x_t^0)))$ 
7:      $x_t^{*0} := \arg \min_{x_t} (C(S_i^t, x_t^0) + V_i^{t-1}(S^{M,x}(S_i^t, x_t^0)))$ 
8:      $S_i^t := S_i^0$ 
9:   end for
10:   $V_i^t := \hat{V}_i^t$ 
11: end while
12: for  $t = 0$  to  $T^{\max} - 1$  do
13:   $x_t^* := x_t^{*0}$ 
14: end for
15: return  $x_t^*$ 

```

### 5.5 Solution Algorithm

In our problem, MILP solvers are able to find a good feasible solution fast, but struggle on improving it further or in proving its optimality. In this section, we design three adaptations to the MILP that are aimed to help a solver find good feasible solutions faster. Furthermore, we design two metaheuristics: (i) a static metaheuristic to solve a single instance of the problem using Math-Heuristic Operators (MHOs), and (ii) a dynamic metaheuristic to solve a re-scheduling instance of the problem using Fixing Criteria (FCs). We now elaborate on the MHOs, FCs, and the workings of each algorithm.

#### 5.5.1 Static Metaheuristic

Our static metaheuristic uses three adaptations to the MILP, iteratively and in a local-search fashion, as shown in the pseudo-code of Algorithm 5. These adaptations, denoted by MHOs, are basically additional constraints in the MILP that can be seen as cutting planes that reduce the feasible space. Since our formulation results in a lot of arcs, our MHOs focus on fixing those arcs in an intuitive way. We now explain each MHO in more detail.

#### Algorithm 5 Static Metaheuristic

```

Require: Graph  $\mathcal{G}$  and associated parameters
1: Initialize best solution
2: while Stopping criterion not met do
3:  Get MHOs (5.7), (5.8), and (5.9)
4:  Build adapted MILP
5:  Solve adapted MILP
6:  if Current solution  $\leq$  Best solution then
7:    Best solution = Current Solution
8:  end if
9: end while
10: return Best solution

```

**MHO 1:** For  $N^{M1}$  random jobs  $r \in \mathcal{V}^R$ , we limit the number of feasible job-ars to at most two, i.e.,  $|\delta^-(r)| \leq 2$  and  $|\delta^+(r)| \leq 2$ . These arcs are from (or to) the two closest locations (i.e., shortest traveling time). In other words, all remaining job-ars are cut out, as shown in (5.7).

$$x_{j,i,k} = 0, \forall k \in \mathcal{K}, j \in \delta^-(r) \setminus \{i\} \mid i = \arg \min_{j \in \delta^-(r)} T_{j,r} \text{ and } i' = \arg \min_{j \in \delta^-(r)} T_{j,r} \quad (5.7a)$$

$$x_{i,j,k} = 0, \forall k \in \mathcal{K}, j \in \delta^+(r) \setminus \{i\} \mid i = \arg \min_{j \in \delta^+(r)} T_{i,j} \text{ and } i' = \arg \min_{j \in \delta^+(r)} T_{i,j} \quad (5.7b)$$

**MHO 2:** For  $N^{M2}$  times, the arc between a job  $r$  of Type 2 and a job  $r'$  of Type 7 with the minimum traveling time is fixed. Remain that the arc is feasible when  $r \in \delta^-(r')$  and

Table 3.4: Confidence intervals (at 95%) of the difference between the benchmark policy and the ADP policy

State	$I_1^C$	$I_2^C$	$I_3^C$	$I_4^C$	$I_5^C$	$I_6^C$
C1	[-7.0%, -4.8%]	[-9.6%, -7.5%]	[-10.3%, -8.4%]	[-6.1%, -4.9%]	[-1.3%, 0.0%]	[-5.9%, -4.5%]
C2	[-9.7%, -8.4%]	[-13.1%, -11.6%]	[-4.8%, -3.3%]	[-3.6%, -1.8%]	[-1.2%, 0.1%]	[-11.6%, -10.4%]
C3	[-2.7%, -1.2%]	[-7.2%, -6.1%]	[-9.1%, -7.4%]	[-3.8%, -2.4%]	[0.5%, 1.7%]	[-7.7%, -6.7%]
C4	[-16.0%, -13.8%]	[-26.5%, -24.6%]	[-6.2%, -4.1%]	[-12.5%, -11.2%]	[-2.2%, -0.7%]	[-8.4%, -7.6%]
C5	[-15.9%, -14.3%]	[-2.0%, -0.9%]	[-10.5%, -8.8%]	[-26.5%, -25.3%]	[-1.0%, 0.1%]	[-10.3%, -9.2%]
C6	[0.5%, 2.1%]	[-5.1%, -3.9%]	[-4.5%, -3.1%]	[-11.1%, -10.0%]	[-2.6%, -1.4%]	[-8.2%, -7.3%]
C7	[-4.7%, -4.0%]	[-4.3%, -3.0%]	[-25.0%, -23.5%]	[-0.6%, 0.4%]	[-12.2%, -9.8%]	[-7.9%, -6.8%]
C8	[-2.9%, -1.7%]	[-17.1%, -16.3%]	[-2.5%, -1.6%]	[-7.5%, -6.7%]	[-0.9%, -0.2%]	[-3.7%, -2.9%]
C9	[-1.5%, -0.3%]	[1.8%, 2.8%]	[5.4%, -3.5%]	[-11.4%, -10.7%]	[3.9%, 5.4%]	[-7.9%, -7.2%]

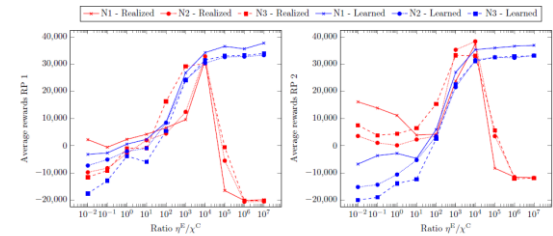


Figure 4.5: Comparison of average rewards (over all modifications) under different ratios  $\eta^R/\lambda^C$

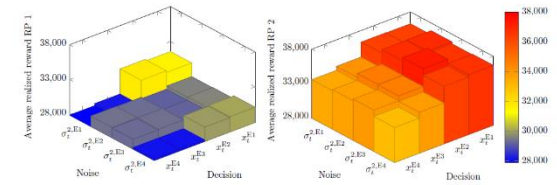


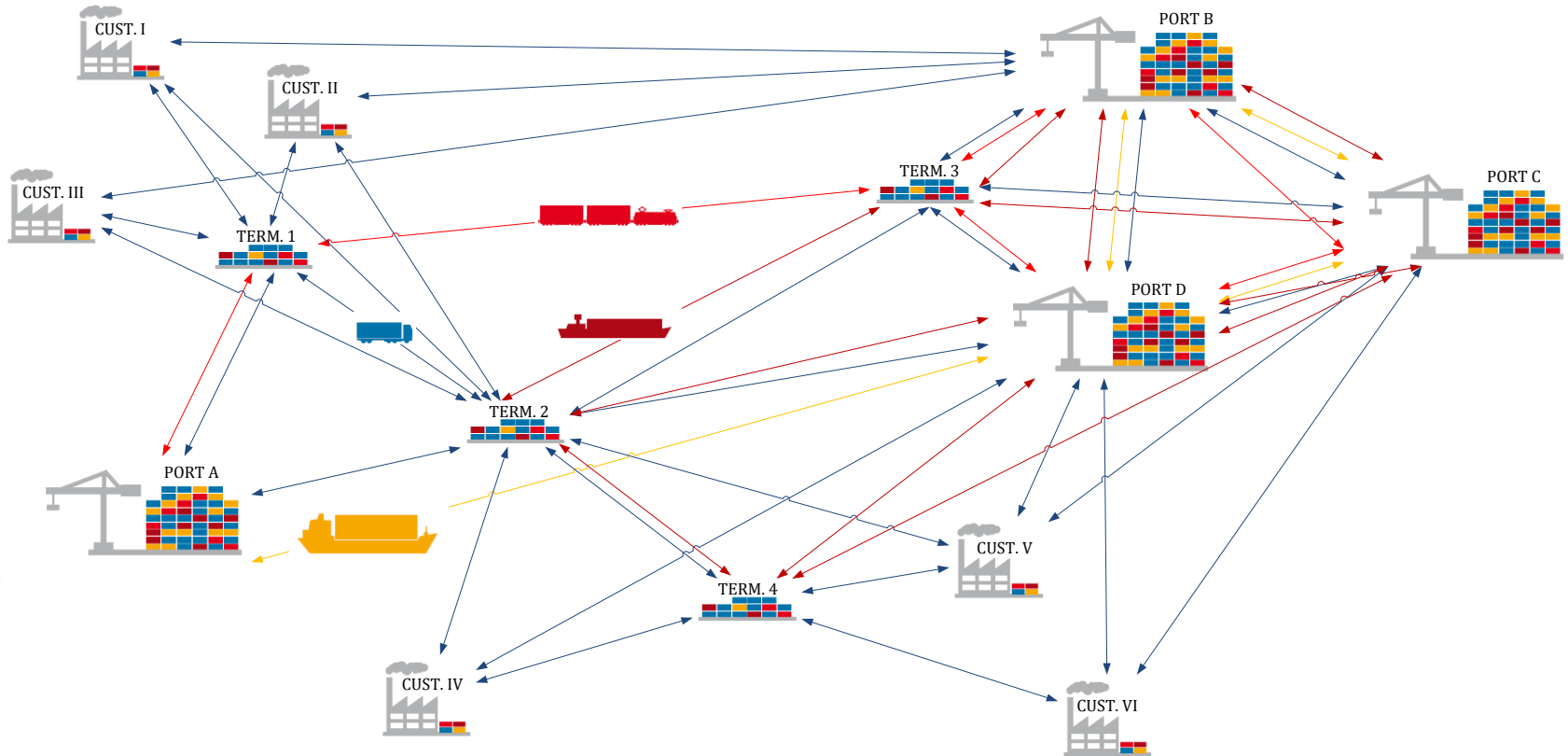
Figure 4.6: Comparison of average rewards (over all networks) for our proposed VPI modifications

## 1. Models

## 2. Algorithms

## 3. Analyses

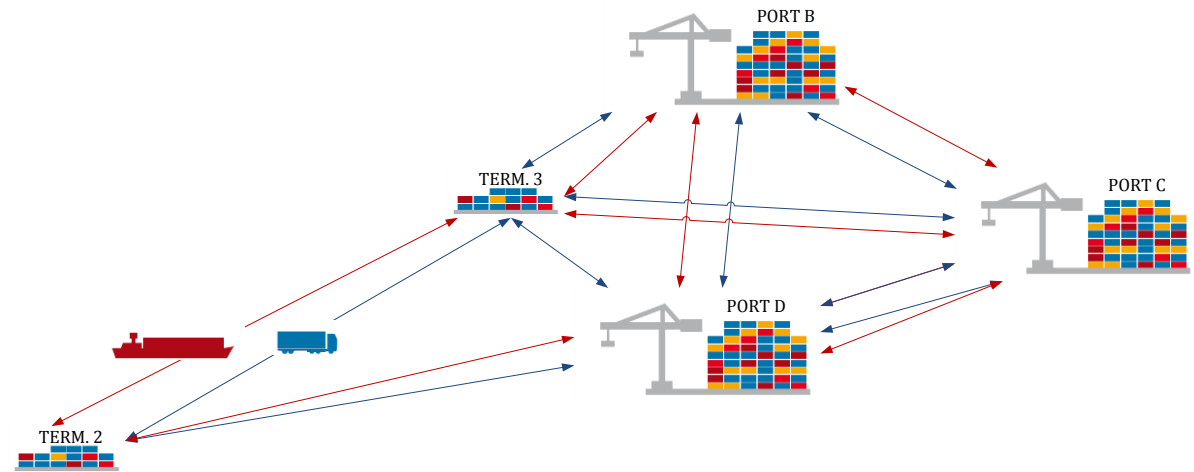
# WE DESIGN ANTICIPATORY SCHEDULING METHODS FOR SYNCHROMODAL TRANSPORT USING OPERATIONS RESEARCH



*\*Source of artwork: European Container Terminals (ECT) – The future of freight transport (2011).*

# I – LONG-HAUL TRANSPORT

## ROUND-TRIPS OF A SINGLE HIGH-CAPACITY MODE



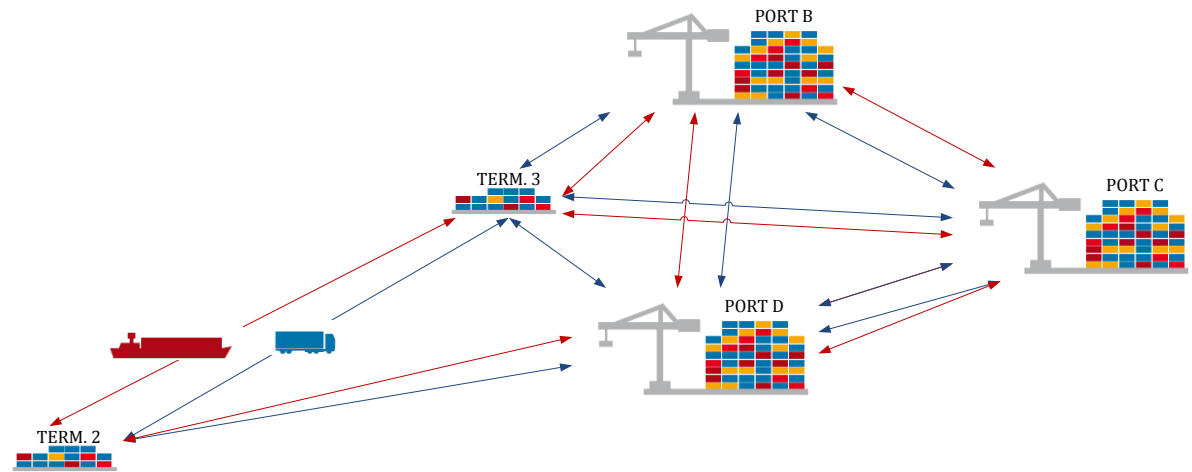
**Challenge:** to balance the consolidation and postponement of freight transport through *time*.

\*Source of artwork: European Container Terminals (ECT) – The future of freight transport (2011).



# I – LONG-HAUL TRANSPORT

## ROUND-TRIPS OF A SINGLE HIGH-CAPACITY MODE

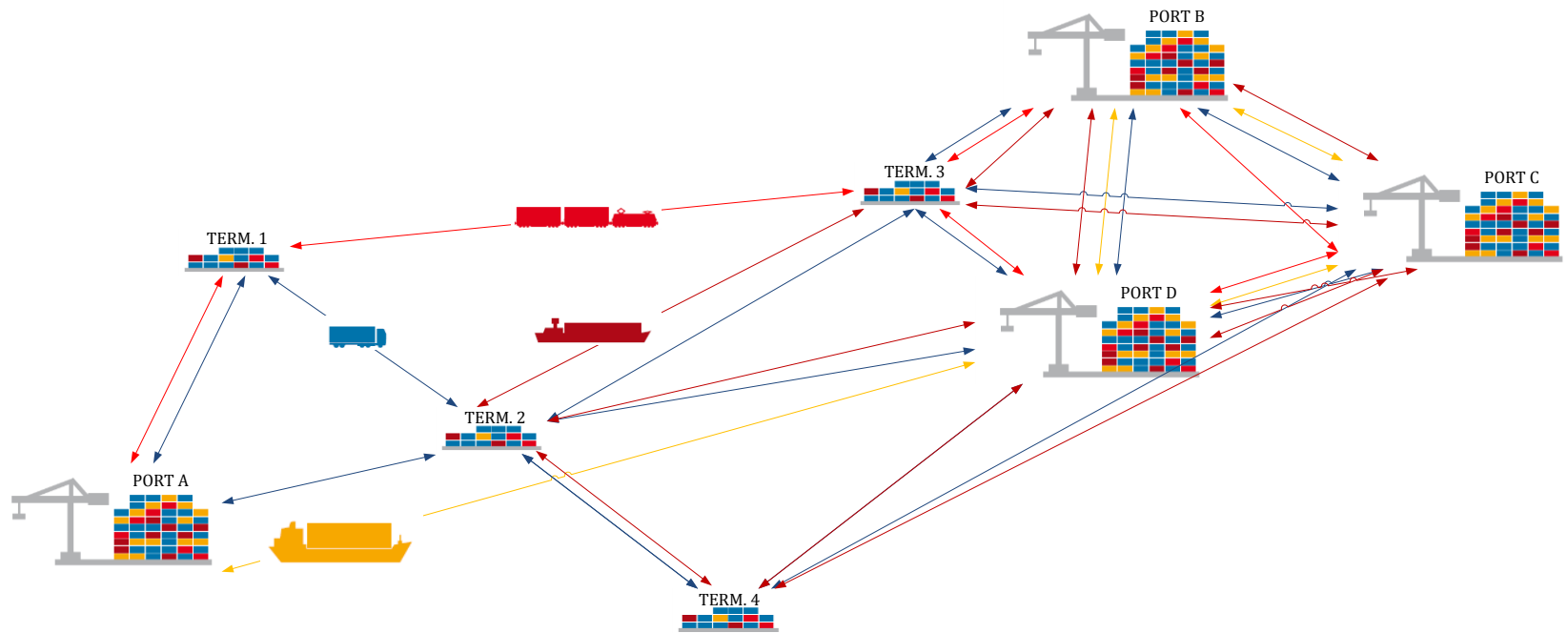


**Results:** Our method achieves up to **26% savings**, especially with **unbalanced destinations** and **pre-announced orders**.

*\*Source of artwork: European Container Terminals (ECT) – The future of freight transport (2011).*

# II – LONG-HAUL TRANSPORT

## MULTIPLE HIGH-CAPACITY MODES WITH TRANSFERS

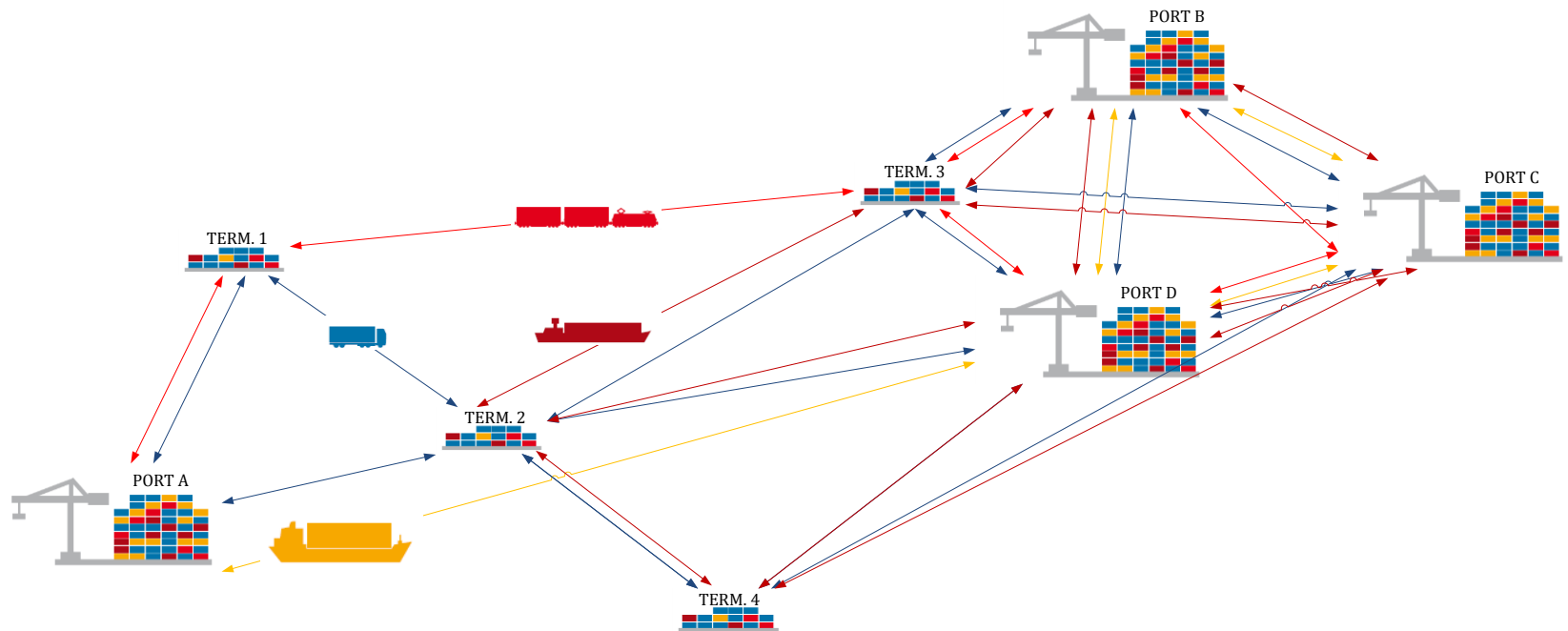


**Challenge:** To balance the consolidation and postponement of freight transport through *time and space*.

\*Source of artwork: European Container Terminals (ECT) – The future of freight transport (2011).

# II – LONG-HAUL TRANSPORT

## MULTIPLE HIGH-CAPACITY MODES WITH TRANSFERS

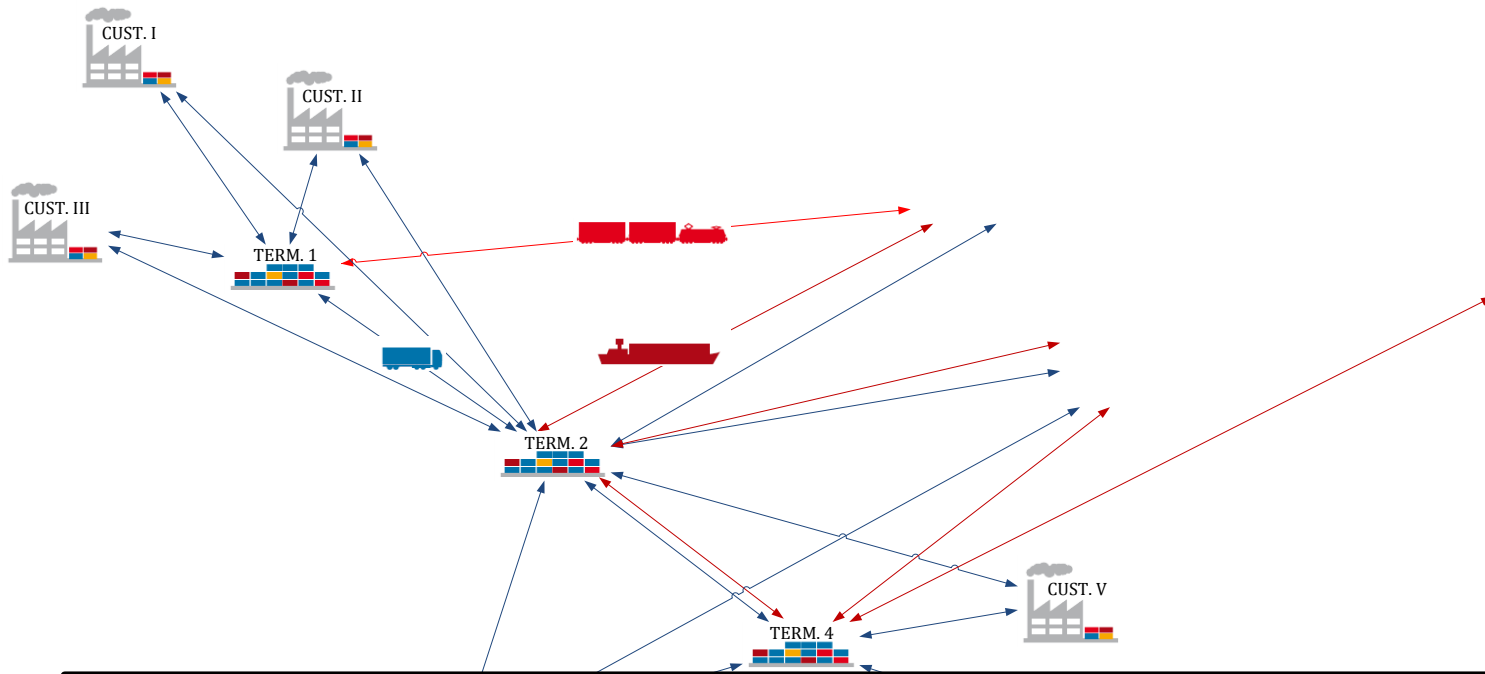


**Results:** Our method achieves more than **20% gains** with **long time-windows**, but *no gains* with *short time-windows*.

\*Source of artwork: European Container Terminals (ECT) – The future of freight transport (2011).

# III – DRAYAGE TRANSPORT

## MULTIPLE LOW-CAPACITY MODES

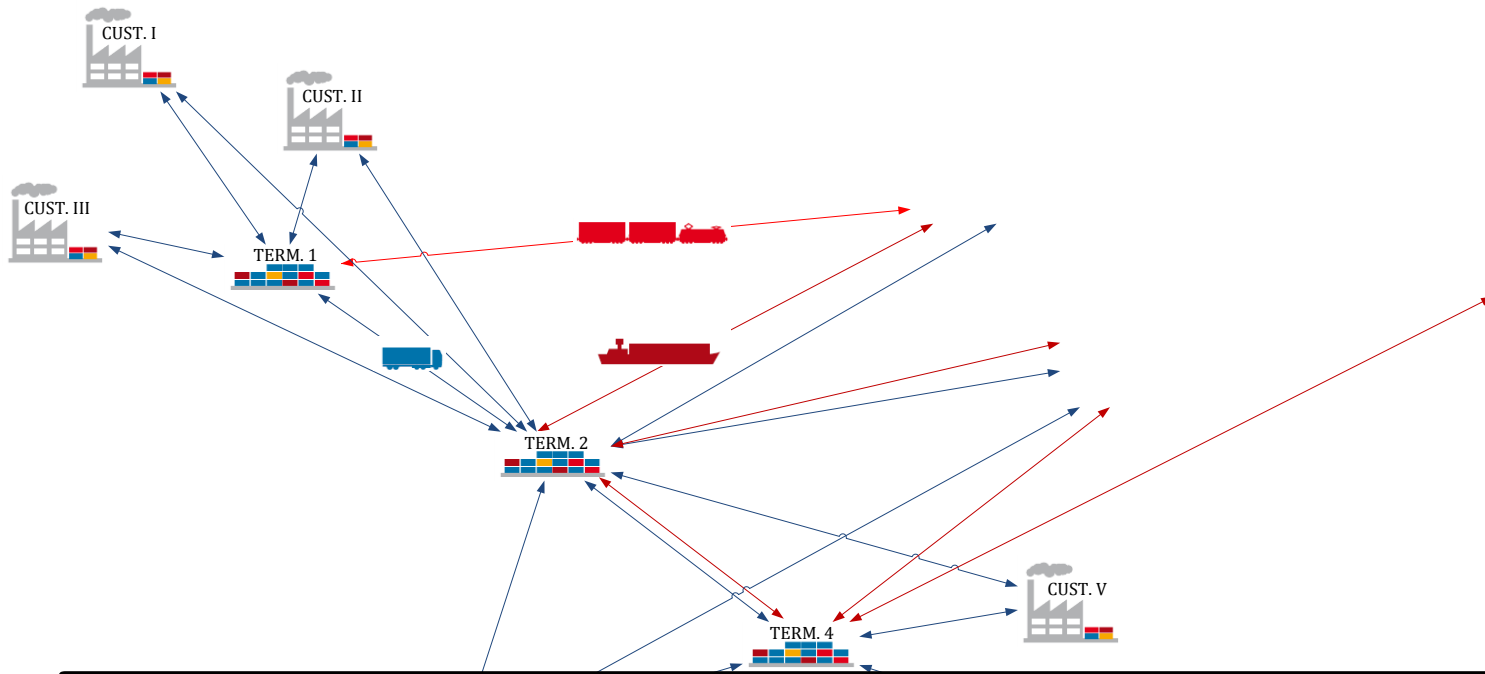


**Challenge:** To weigh the immediate routing costs against the ***terminal assignment*** costs.

\*Source of artwork: European Container Terminals (ECT) – The future of freight transport (2011).

# III – DRAYAGE TRANSPORT

## MULTIPLE LOW-CAPACITY MODES

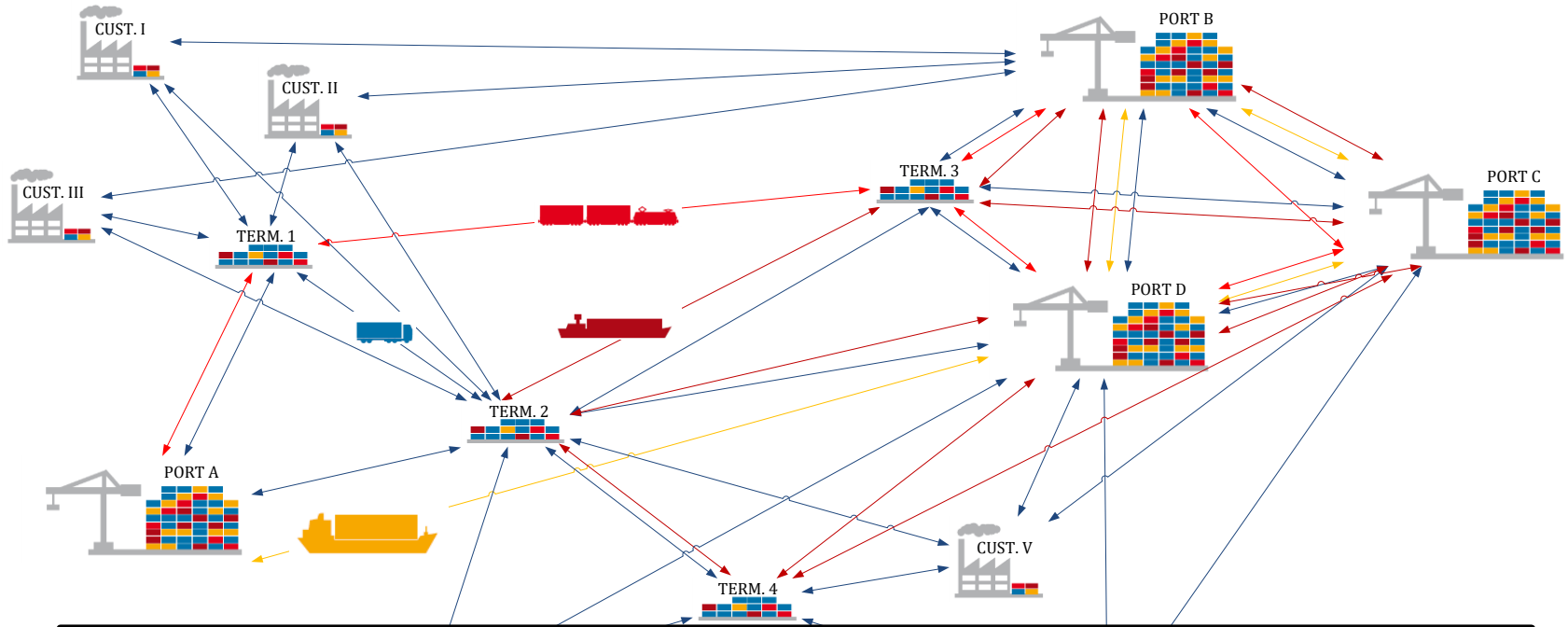


**Results:** Our method achieves up to **4% savings**, especially with **clustered locations** and **short time-windows**.

*\*Source of artwork: European Container Terminals (ECT) – The future of freight transport (2011).*

# IV – INTEGRATED LONG-HAUL AND DRAYAGE TRANSP.

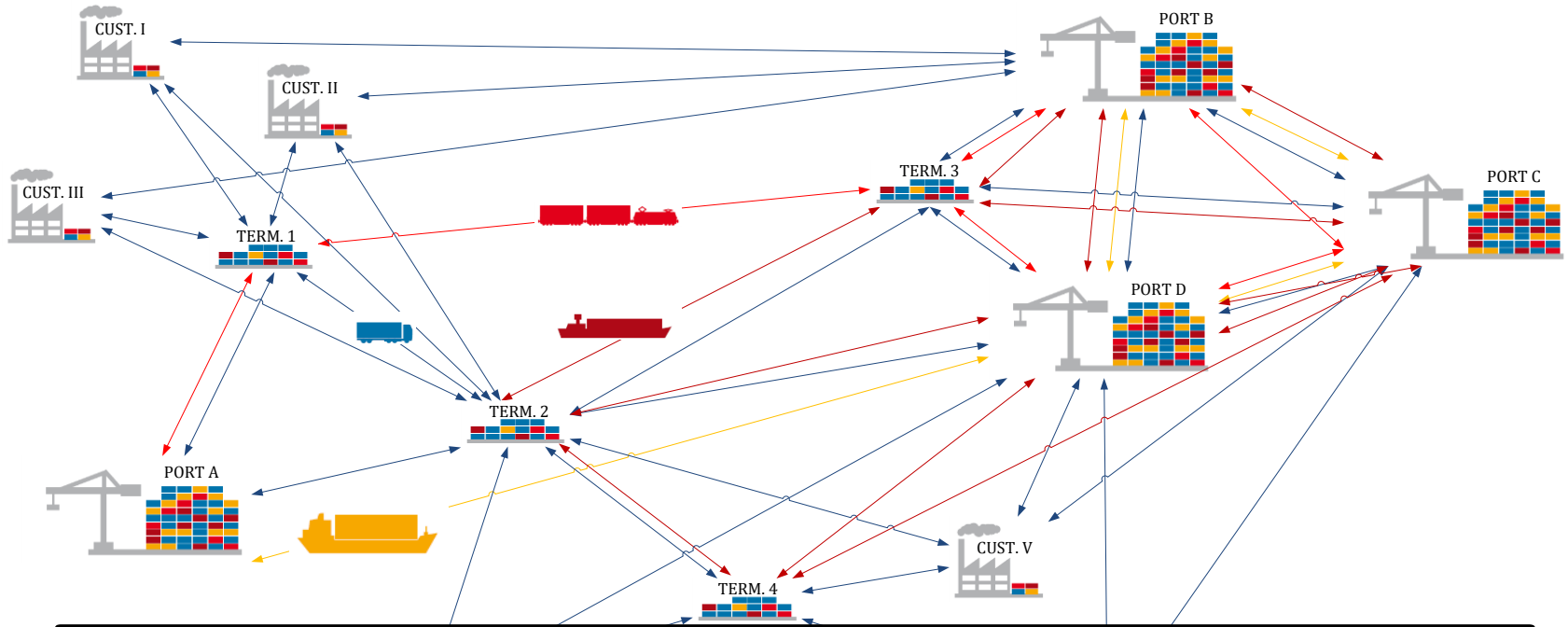
## THE ENTIRE NETWORK



**Challenge:** To optimize *network-wide performance through time* long-haul and drayage transport schedules

\*Source of artwork: Europe Container Terminals "The future of freight transport". [www.ect.nl](http://www.ect.nl)

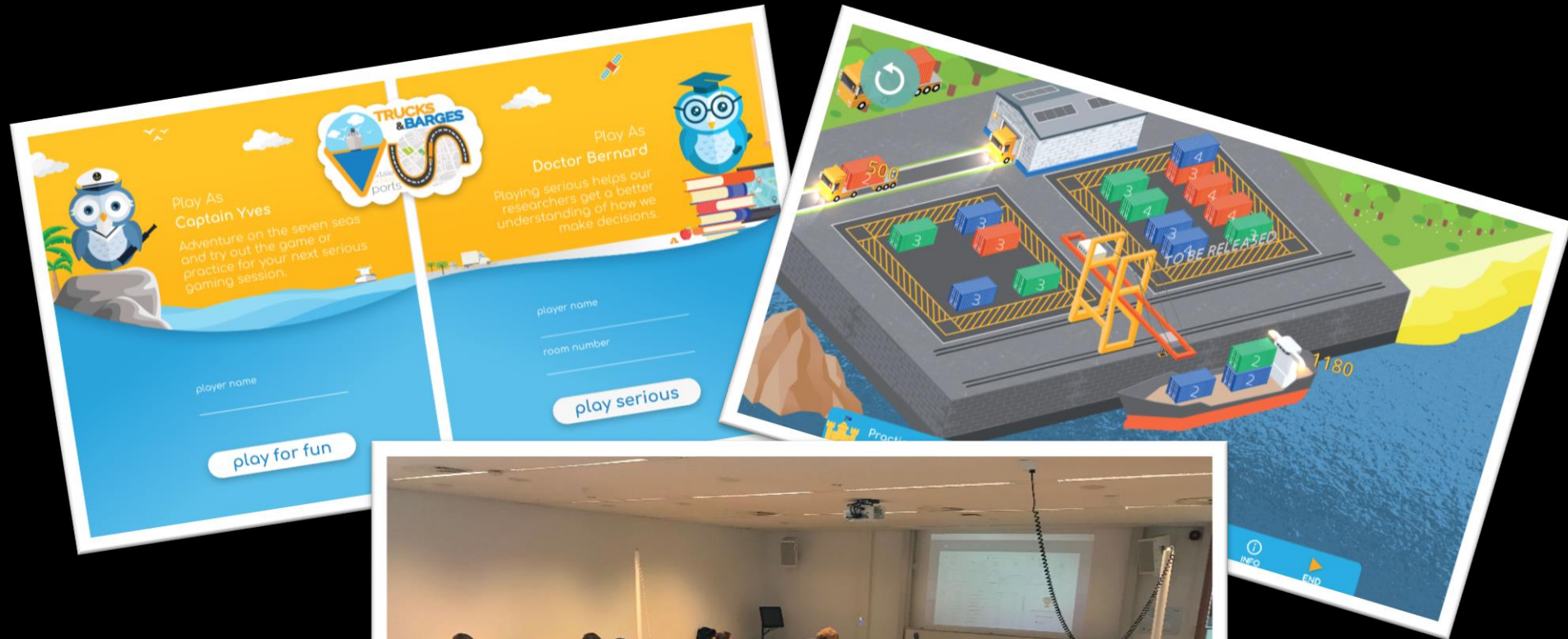
# IV – INTEGRATED LONG-HAUL AND DRAYAGE TRANSP. THE ENTIRE NETWORK



**Results:** Our method achieves up to **38% savings network-wide**, but it may sacrifice the performance of one part.

*\*Source of artwork: Europe Container Terminals "The future of freight transport". [www.ect.nl](http://www.ect.nl)*

# RAISING AWARENESS – SERIOUS GAMING






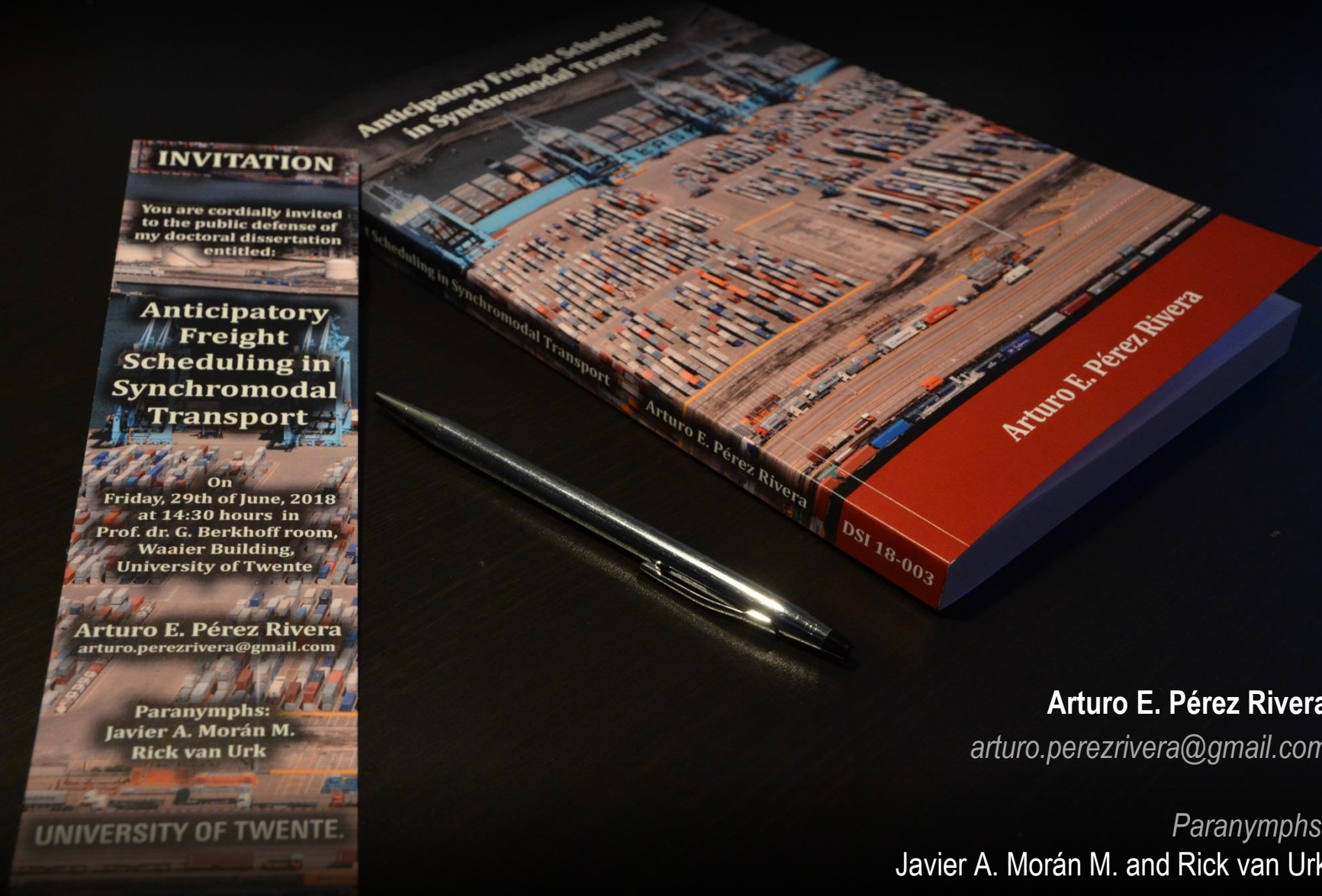


# TAKEAWAYS

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-  We design anticipatory scheduling methods for synchromodal transport to take advantage of the new consolidation opportunities that appear over the network and over time.
- Using our methods pays off the most with pre-announced freights that have long-time windows, and the least with urgent freights and balanced networks.
- ● Integrating anticipatory scheduling methods of drayage and long-haul transport improves the performance of the network as a whole, but might sacrifice the performance of one of the processes.

Reception @ Rico Latino (De Heurne 19b) – 21:00 – I hope to see you all there!



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