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Synchromodality in the Physical Internet

Real-time Switching in a Multimodal Network with Stochastic Transit Times

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A deep decarbonization of the logistics industry is needed.

- Enormous amount of CO_2 emissions from the freight transportation sector

- Modal shift towards less carbon-intensive transportation modes

- The Physical Internet

  Connect logistics networks into an integrated network

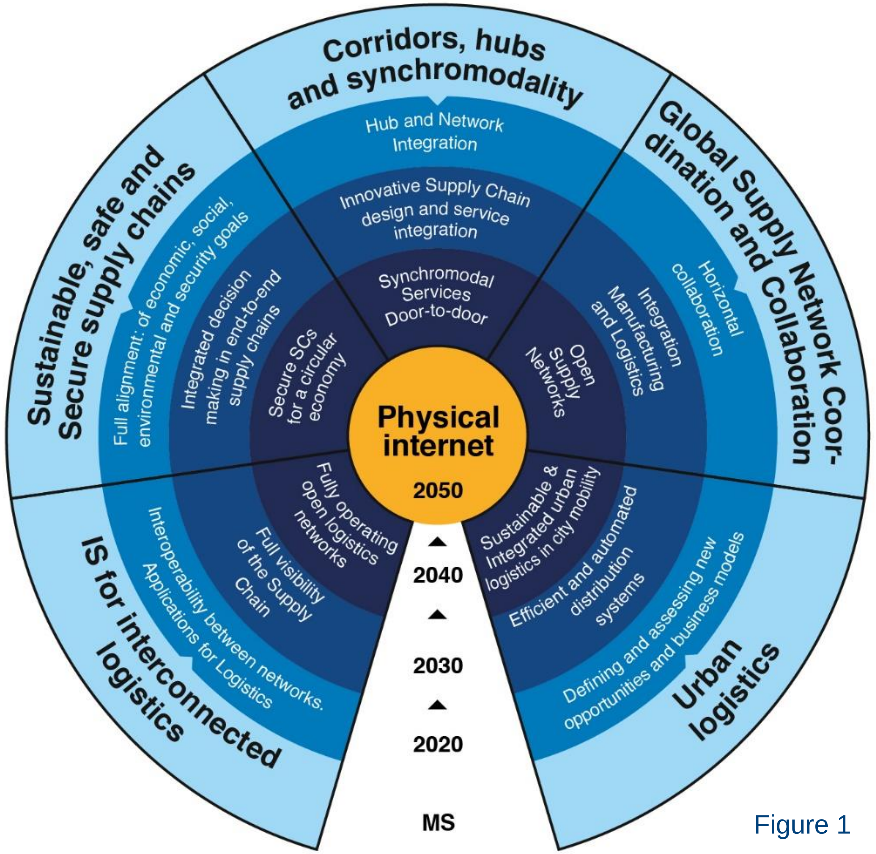

Figure 1

Figure 1. Adapted from *Roadmap: Corridors, Hubs and Synchromodality*, by ETP-Alice. Retrieved from http:// etp- logistics.eu.

Synchromodality offers a solution to reduce emissions.

- Enormous amount of CO_2 emissions from the freight transportation sector

- Modal shift towards less carbon-intensive transportation modes

- The Physical Internet ➢ Synchromodality

  Connect logistics networks into an integrated network

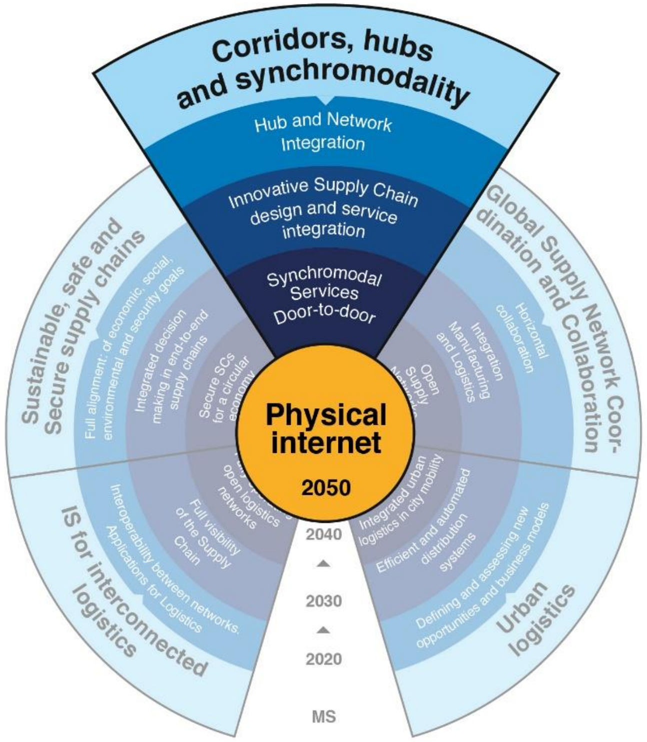

Figure 1. Adapted from *Roadmap: Corridors, Hubs and Synchromodality*, by ETP-Alice. Retrieved from http:// etp- logistics.eu.

Figure 1

Synchromodality - Towards the Physical Internet.

- Multiple transportation modes

- Real-time information

➢ Select the best transportation mode at all times

➢ Use modalities more efficiently and exploit all advantages

Synchromodality efficiently copes with uncertainty in transit times.

Synchromodality in a network with **stochastic transit times**

- Unreliability in transportation system
- Optimal transportation decision given the transit time outcome

Synchromodality efficiently copes with uncertainty in transit times.

Synchromodality in a network with **stochastic transit times**

- Unreliability in transportation system
- Optimal transportation decision given the transit time outcome

Research objective

- Develop synchromodal planning model to construct optimal transportation routes
- Insights in the advantages of synchromodality

Cost

Service quality

Sustainability

Synchromodality efficiently copes with uncertainty in transit times.

Synchromodality in a network with **stochastic transit times**

- Unreliability in transportation system
- Optimal transportation decision given the transit time outcome

Research objective

- Develop synchromodal planning **model** to construct optimal transportation routes
- **Insights** in the advantages of synchromodality

Cost Service quality Sustainability

Our model constructs optimal transportation routes given the stochastic transit times.

Input

- Multimodal network
- Set of orders

Optimization model

- Construct optimal transportation routes
- MILP

Output

- Decision guide conditional on transit time outcome

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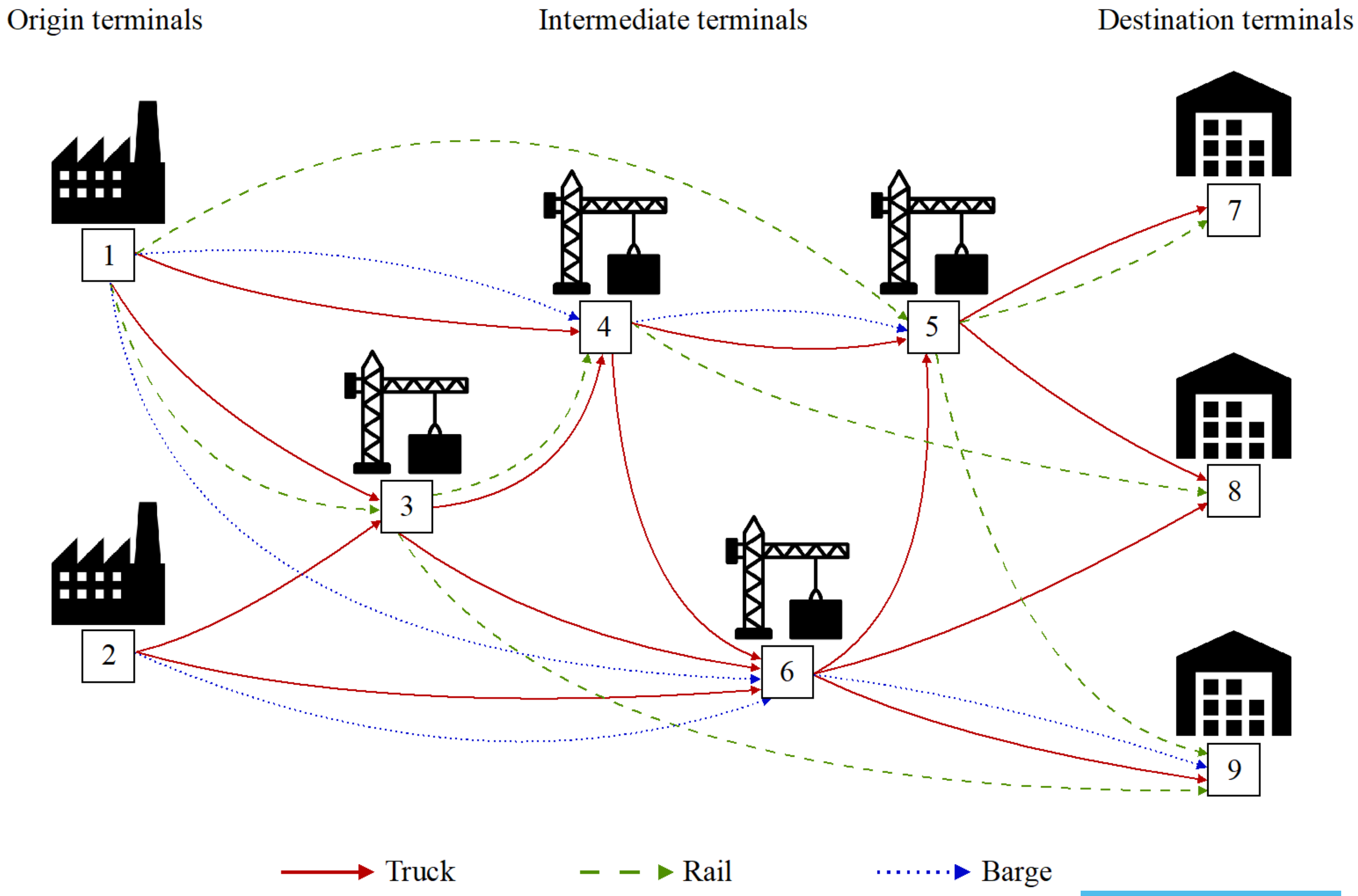
Input of the model

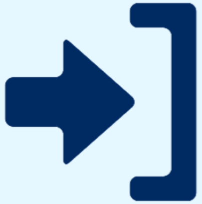


Input

- Multimodal network
- Set of orders

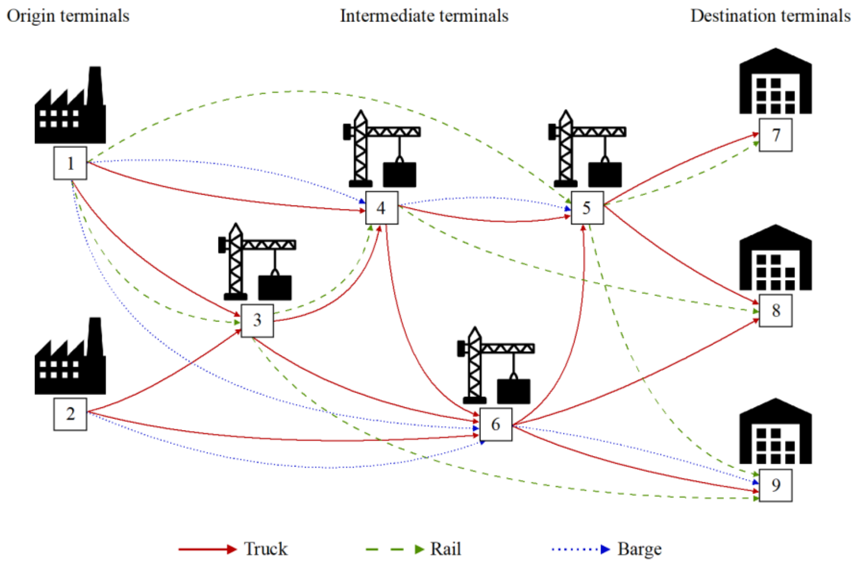
➢ Input parameters

Input of the model: stochasticity is modeled through scenarios.



Input

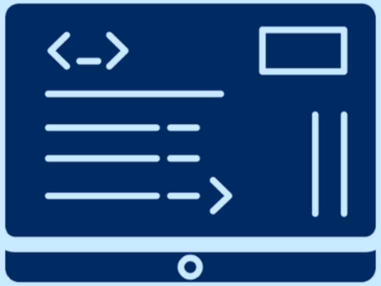
- Multimodal network
- Set of orders
- ➢ Input parameters



Transit time stochasticity

- Transit time scenarios
- Probability distribution

The optimization model is formulated as a mixed-integer linear programming problem.



Optimization model

- Construct optimal transportation routes
- MILP

- Construct optimal transportation routes
  - Routing decisions
  - Stochasticity: adapt routes to real-time information

- Mixed-integer linear programming problem

Minimize - Leg transportation cost
- Terminal transshipment cost
- Overdue penalty cost

Low cost (leg transportation cost, terminal transshipment cost)

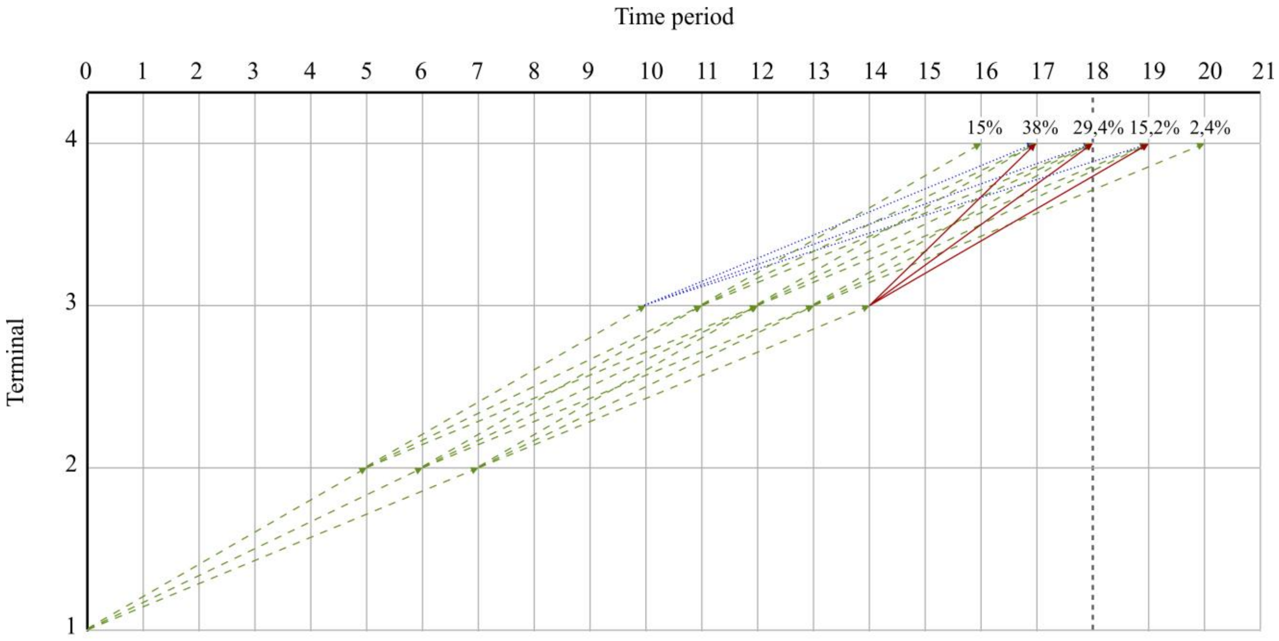
On-time delivery (overdue penalty cost)

Output of the model

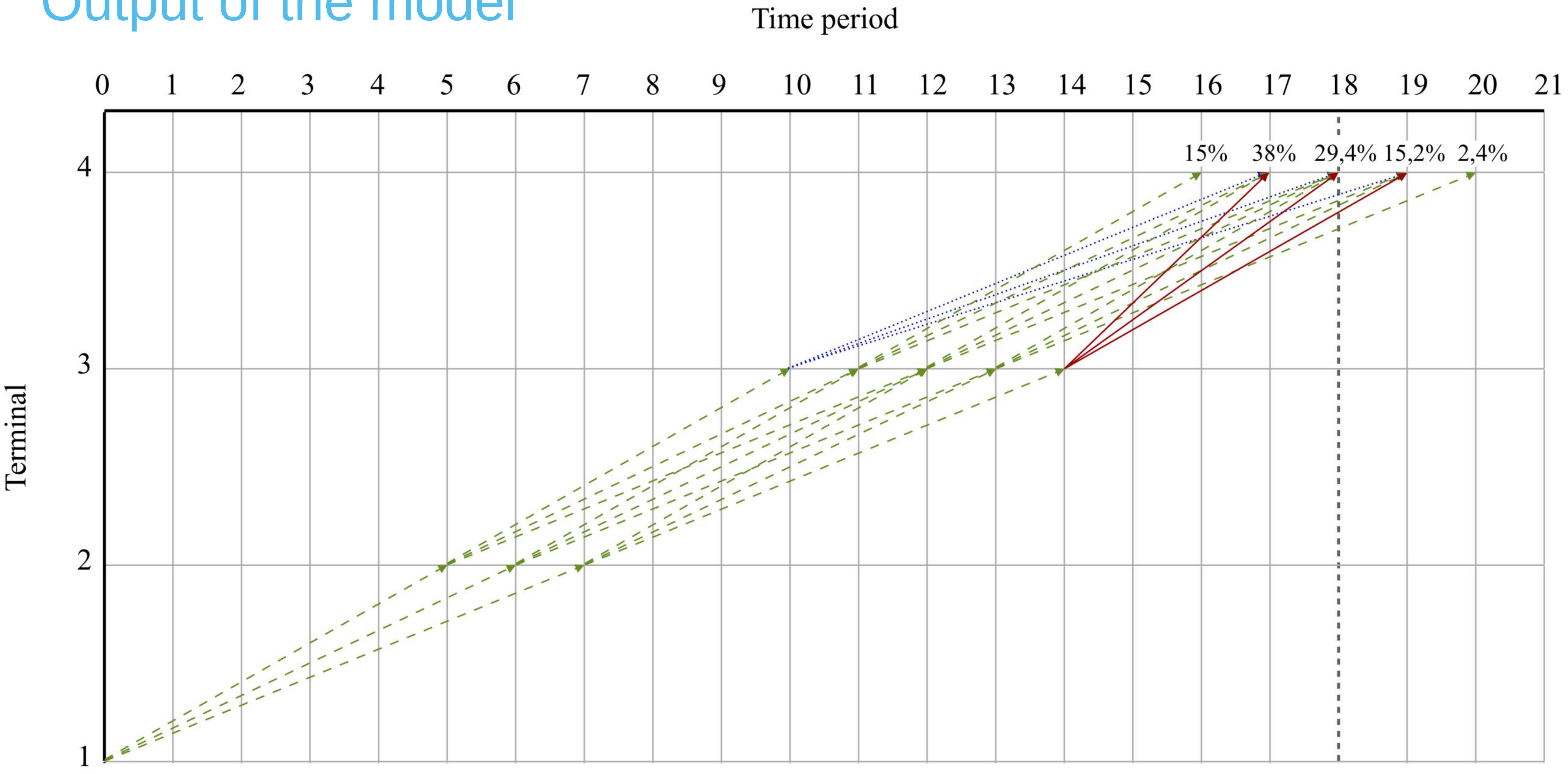
Output

- Decision guide conditional on the transit time outcome

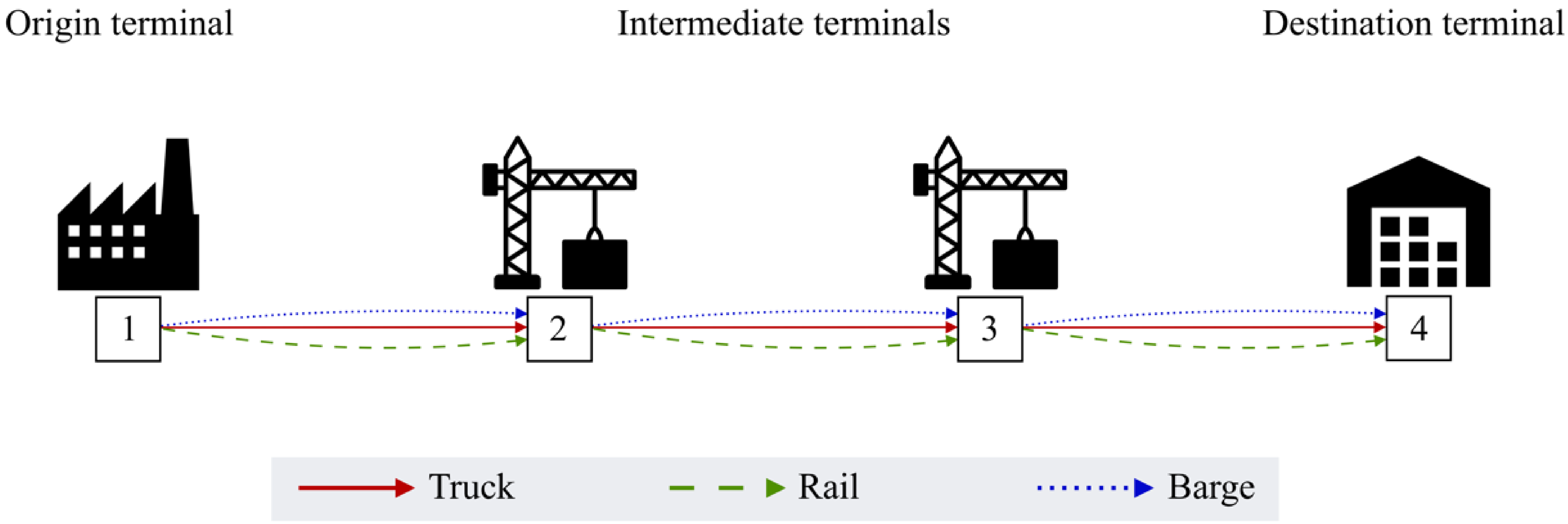
➢ Which decision to take in a terminal, given the time period in which the decision is to be made



Output of the model



Numerical study

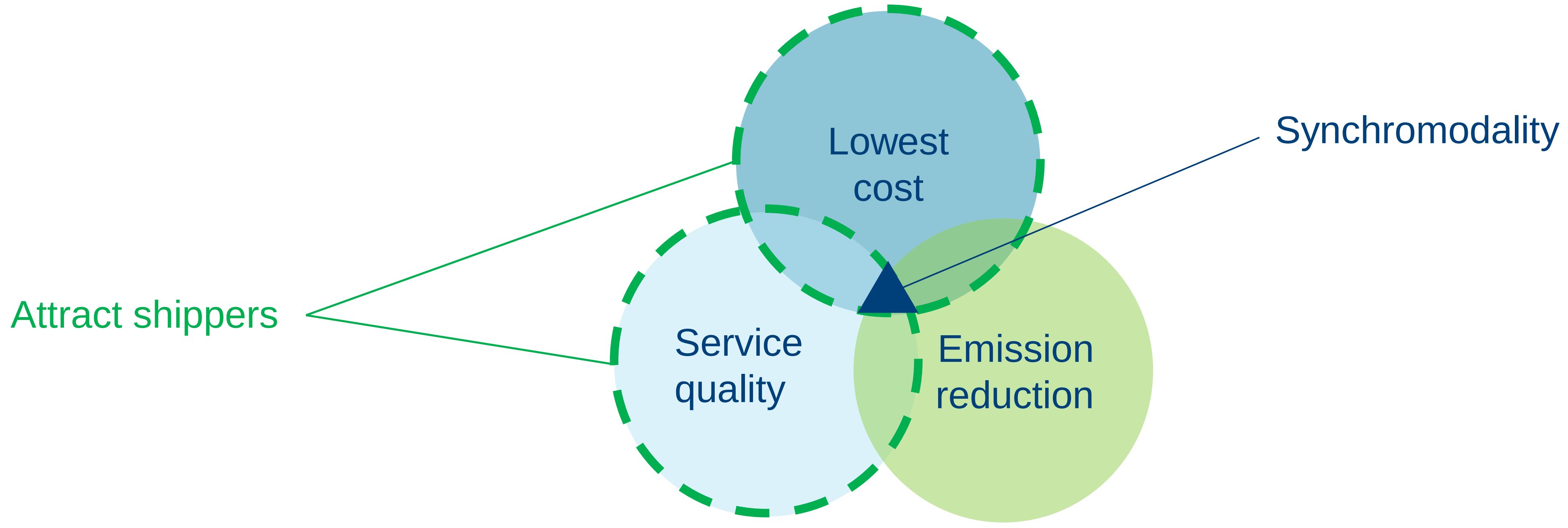


Numerical study - Performance analysis.

Common practice	One mode	Multiple modes	Real-time information
▪ Unimodal road transportation	x		
▪ Unimodal rail transportation	x		
▪ Unimodal barge transportation	x		
▪ Multimodal transportation		x	
▪ Synchromodal transportation		x	x

Value of real-time planning

Synchromodality performs well in terms of cost, service quality and environmental impact.



- Synchromodality offers a combination of advantages that allows to achieve sustainable freight transportation services at a favorable price and service quality.

Numerical study – Sensitivity analyses.

Penalty per period of late delivery

Transshipment cost in terminals

Carbon tax per ton CO_2

Reliability of transportation modes

Numerical study – Sensitivity analyses.

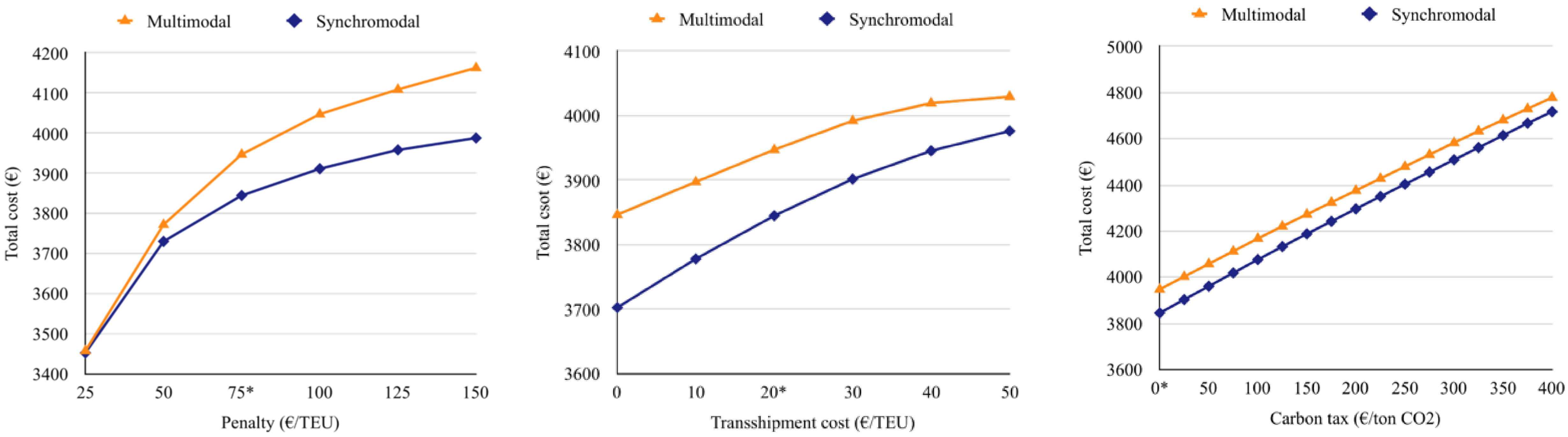
Penalty per period of late delivery

Transshipment cost in terminals

Carbon tax per ton CO_2

Reliability of transportation modes

Numerical study – Impact of changing cost parameters.

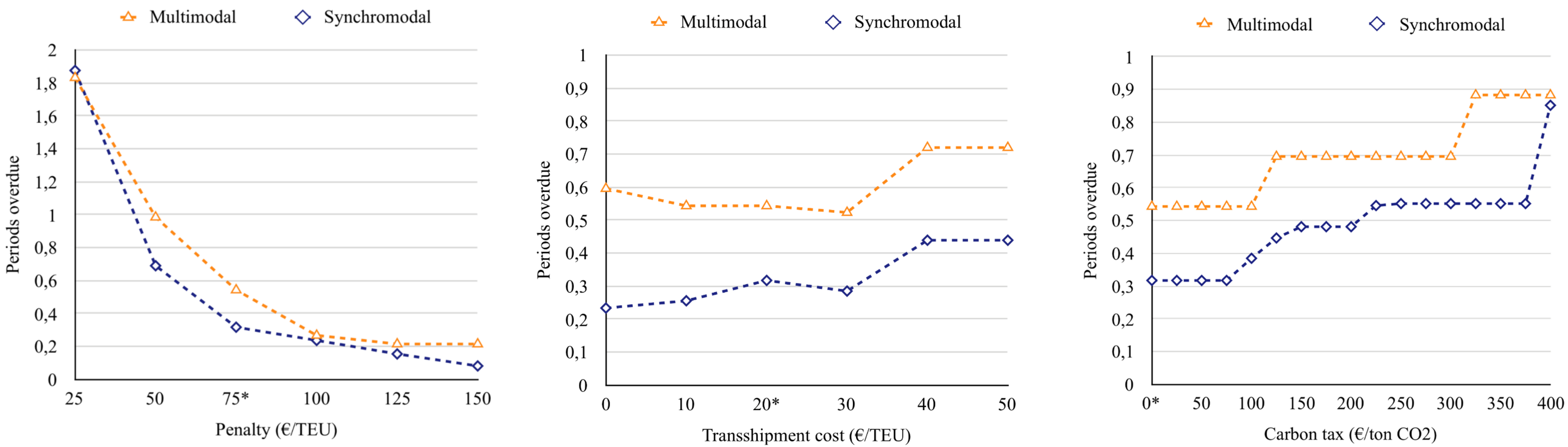


Synchromodality > Multimodality

- Cost
- Service quality

regardless of the parameter value

Numerical study – Impact of changing cost parameters.



Synchromodality > Multimodality

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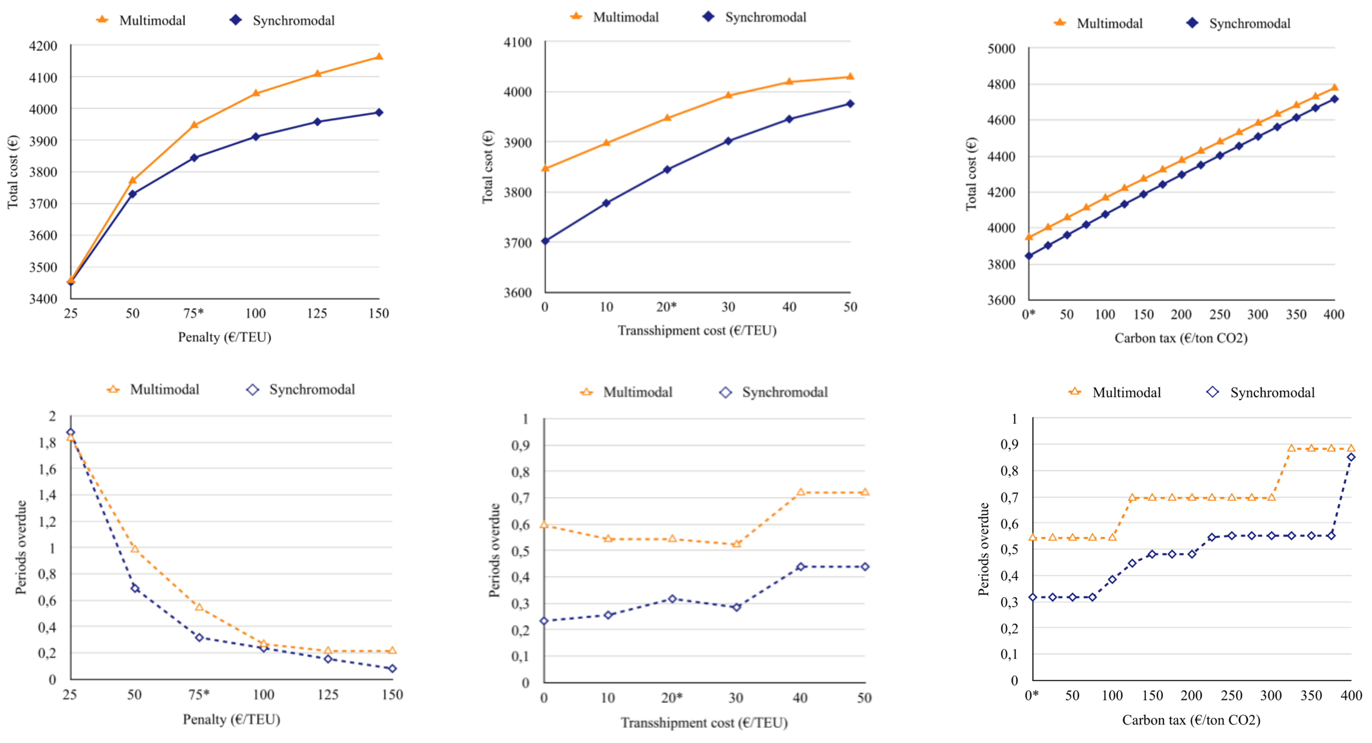
Numerical study – Impact of changing cost parameters.



Synchromodality > Multimodality

- Cost
- Service quality

regardless of the parameter value

➢ Value of real-time information

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Numerical study – Impact of carbon tax.

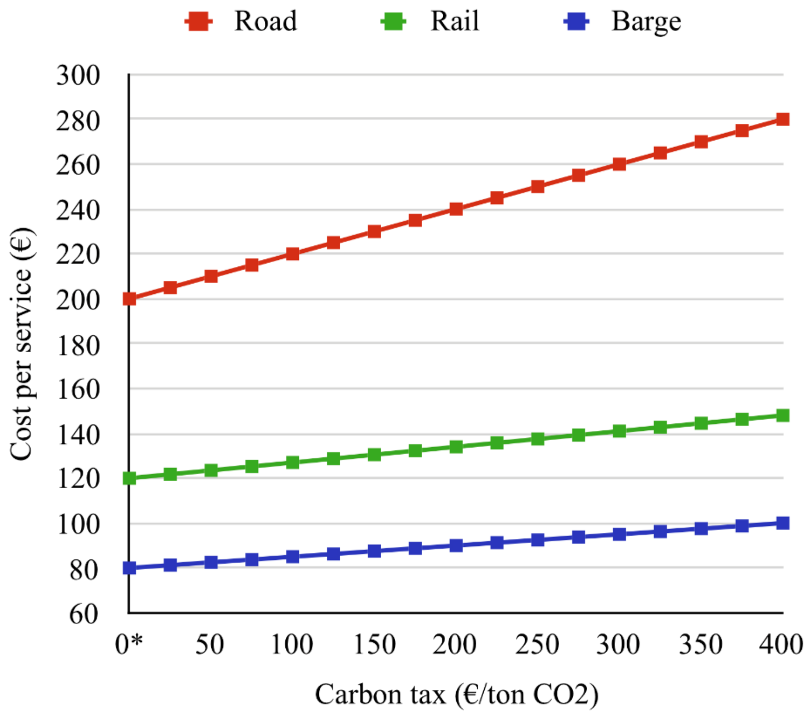
Penalty per period
of late delivery

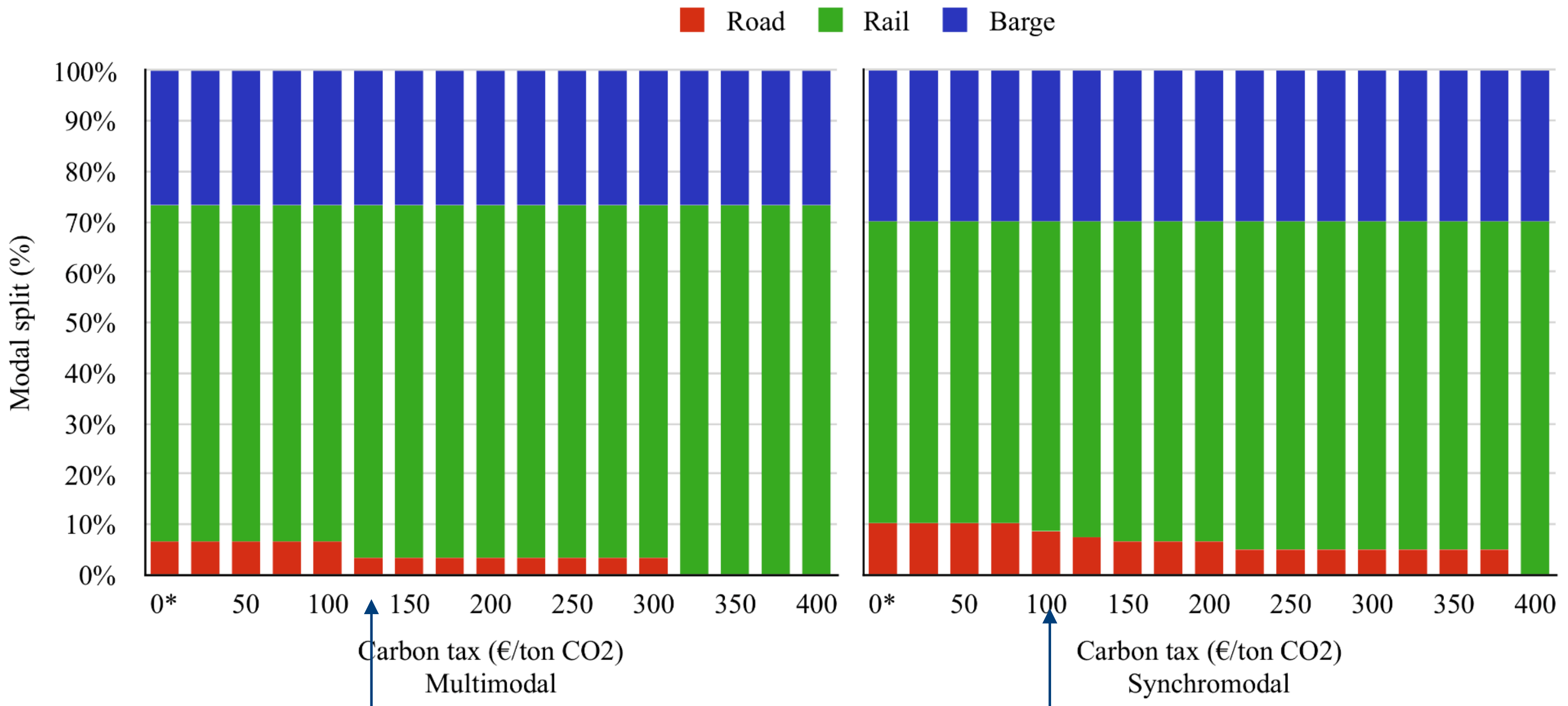
Transshipment cost
in terminals

**Carbon tax
per ton CO_2**

Reliability of
transportation modes

Numerical study – Impact of carbon tax.





125 € / ton CO_2

100 € / ton CO_2

Numerical study – Impact of reliability.

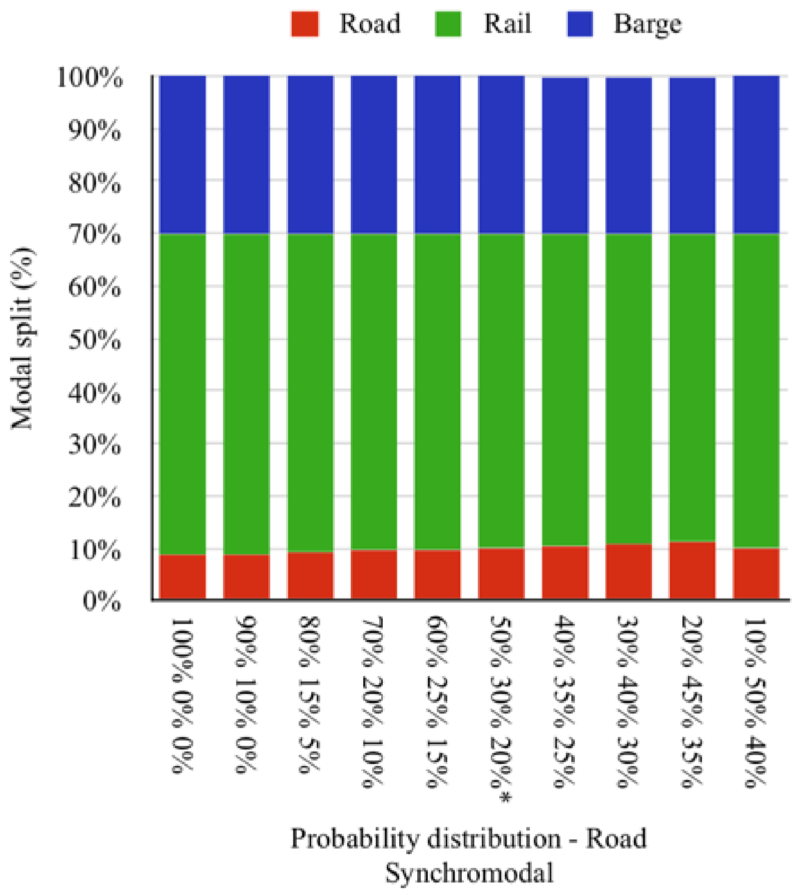
Penalty per period
of late delivery

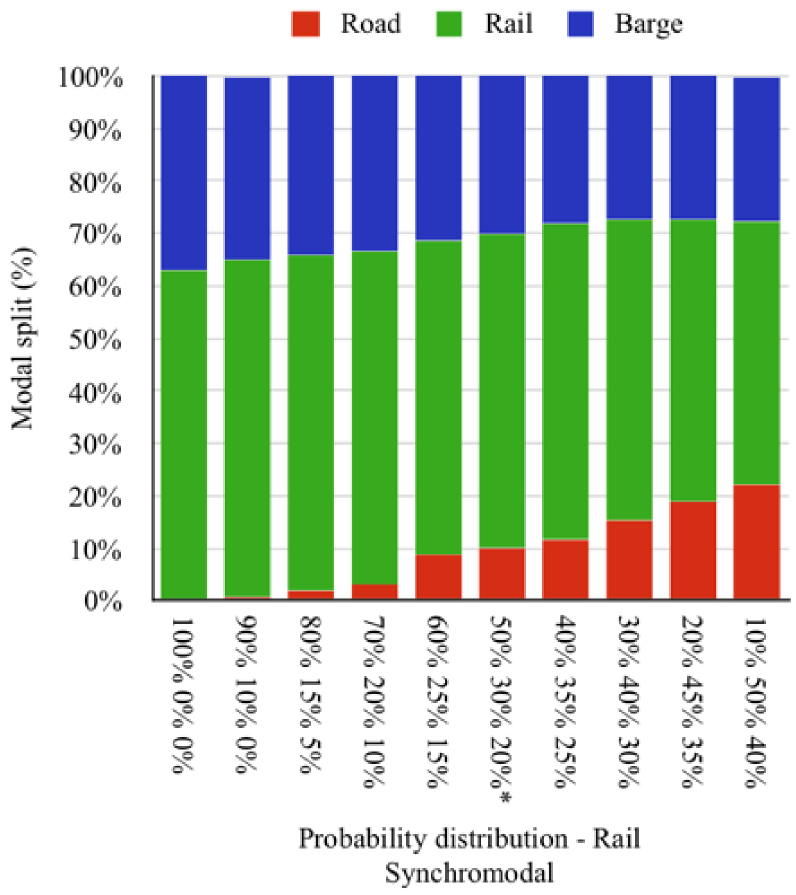
Transshipment cost
in terminals

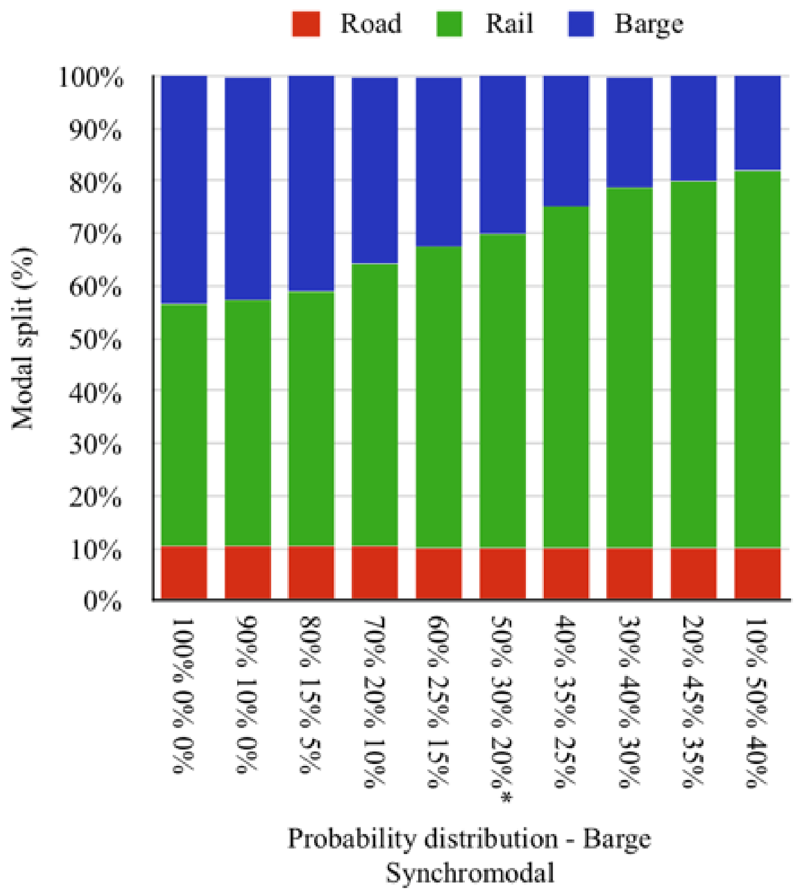
Carbon tax
per ton CO_2

**Reliability of
transportation modes**

Numerical study – Impact of reliability.







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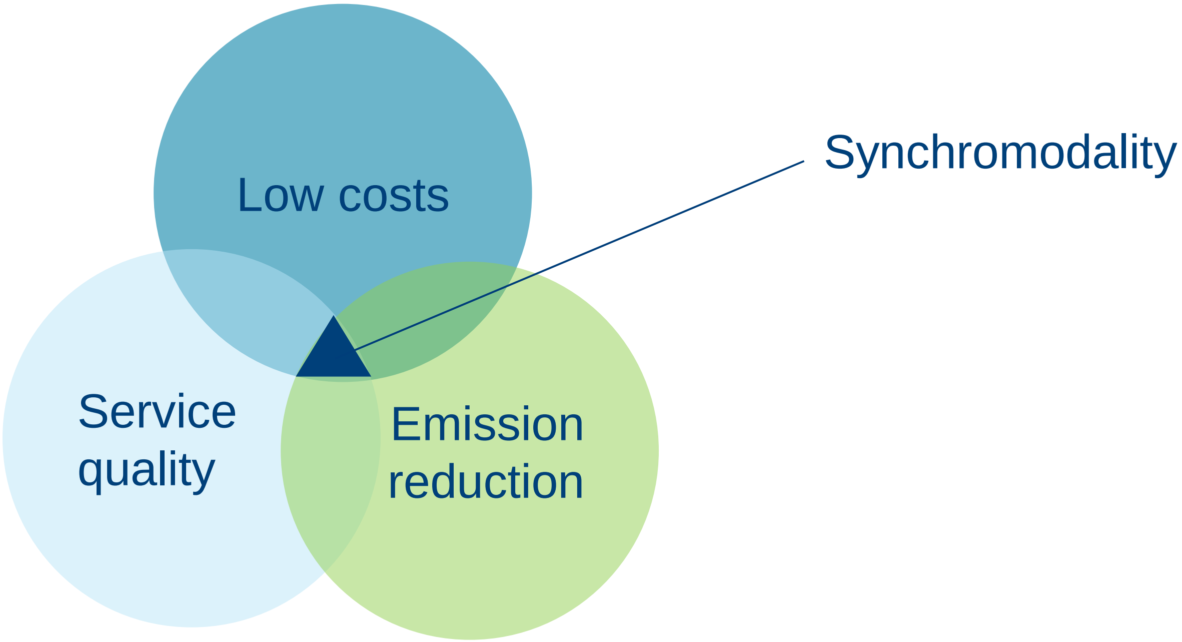
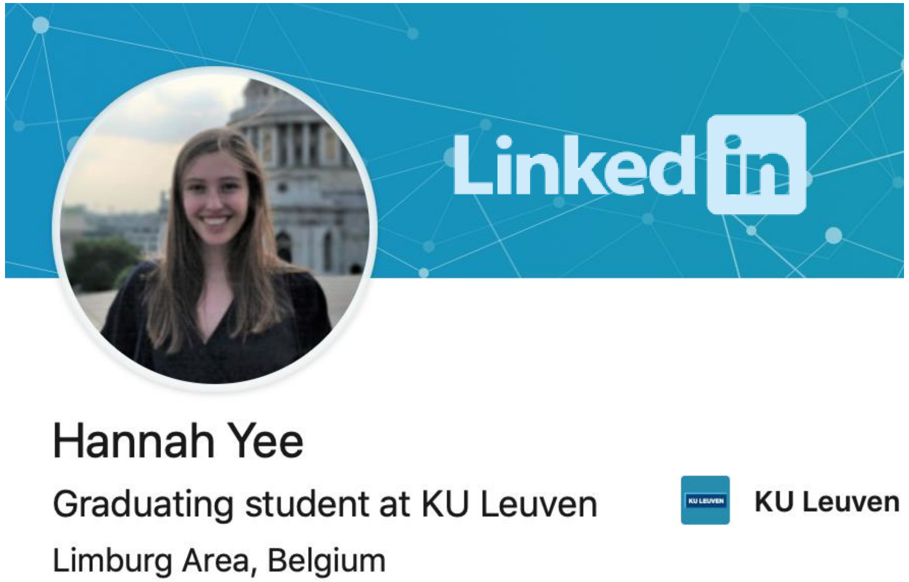
Conclusion

We developed a synchromodal planning model to construct optimal transportation routes in a multimodal network with stochastic transit times.

Synchromodality offers a combination of advantages that allows to achieve sustainable freight transportation services at a favorable price and service quality.





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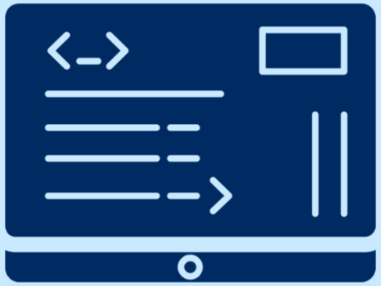
Additional information

Methodology

Objective function

The model minimizes total cost.



Optimization model

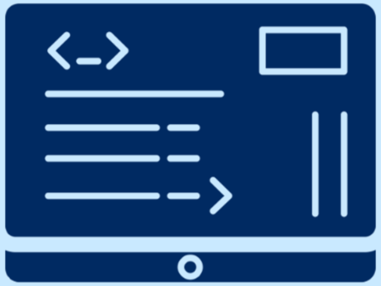
- Construct optimal transportation routes
- MILP

Objective function

Minimize

$$\sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[C^V]^n_{i,j,m,0} + \sum_{n\in\mathcal{O}}\sum_{g,m\in\mathcal{M}} E[C^T]^n_{i,g,m,0} + \sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[\rho]^n_{i,j,m,0}$$

The model minimizes total cost.



Optimization model

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variable leg transportation cost

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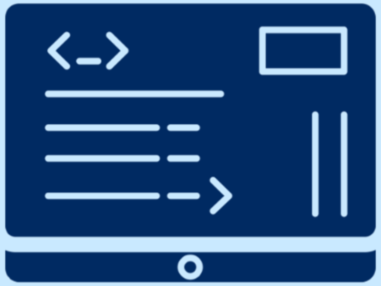
The model minimizes total cost.



Optimization model

- Construct optimal transportation routes
- MILP

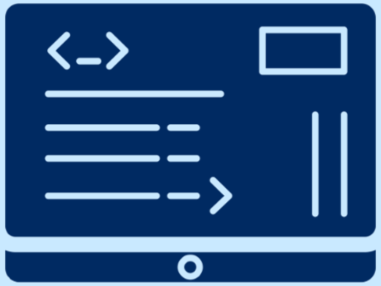
Objective function

$$\mathit{Minimize}$$

$$\sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[C^V]^n_{i,j,m,0} + \sum_{n\in\mathcal{O}}\sum_{g,m\in\mathcal{M}} E[C^T]^n_{i,g,m,0} + \sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[\rho]^n_{i,j,m,0}$$

terminal transshipment cost

The model minimizes total cost.



Optimization model

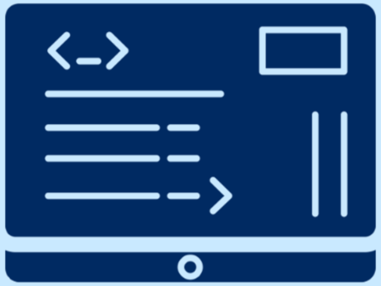
- Construct optimal transportation routes
- MILP

Objective function

$$\mathit{Minimize}$$

$$\sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[C^V]^n_{i,j,m,0} + \sum_{n\in\mathcal{O}}\sum_{g,m\in\mathcal{M}} E[C^T]^n_{i,g,m,0} + \underbrace{\sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[\rho]^n_{i,j,m,0}}_{\text{overdue penalty cost}}$$

The model minimizes total cost.



Optimization model

- Construct optimal transportation routes
- MILP

Objective function

$$Minimize$$

$$\underbrace{\sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[C^V]^n_{i,j,m,0}}_{\text{variable leg transportation cost}} + \underbrace{\sum_{n\in\mathcal{O}}\sum_{g,m\in\mathcal{M}} E[C^T]^n_{i,g,m,0}}_{\text{terminal transshipment cost}} + \underbrace{\sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[\rho]^n_{i,j,m,0}}_{\text{overdue penalty cost}}$$

The model minimizes total cost.

Optimization model

- Construct optimal transportation routes
- MILP

Objective function

$$\textit{Minimize}$$

$$\underbrace{\sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[C^V]^n_{i,j,m,0}}_{\text{variable leg transportation cost}} + \underbrace{\sum_{n\in\mathcal{O}}\sum_{g,m\in\mathcal{M}} E[C^T]^n_{i,g,m,0}}_{\text{terminal transshipment cost}} + \underbrace{\sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[\rho]^n_{i,j,m,0}}_{\text{overdue penalty cost}}$$

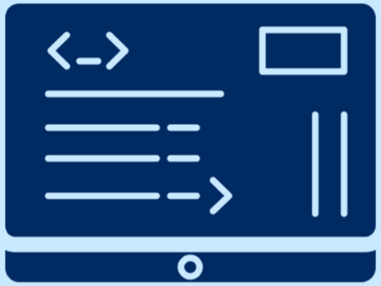
variable leg transportation cost

terminal transshipment cost

overdue penalty cost

low cost (variable leg transportation cost + terminal transshipment cost)

The model minimizes total cost.



Optimization model

- Construct optimal transportation routes
- MILP

Objective function

$$\mathit{Minimize}$$

$$\sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[C^V]^n_{i,j,m,0} + \sum_{n\in\mathcal{O}}\sum_{g,m\in\mathcal{M}} E[C^T]^n_{i,g,m,0} + \sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[\rho]^n_{i,j,m,0}$$

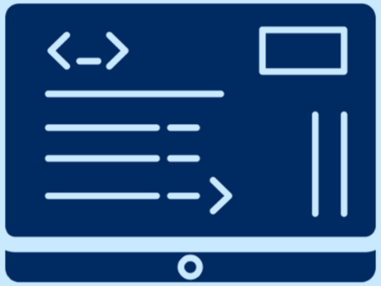
variable leg transportation cost

terminal transshipment cost

overdue penalty cost

on-time delivery

The model minimizes total cost.



Optimization model

- Construct optimal transportation routes
- MILP

Objective function

Minimize

$$\underbrace{\sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[C^V]^n_{i,j,m,0}}_{\text{variable leg transportation cost}} + \underbrace{\sum_{n\in\mathcal{O}}\sum_{g,m\in\mathcal{M}} E[C^T]^n_{i,g,m,0}}_{\text{terminal transshipment cost}} + \underbrace{\sum_{n\in\mathcal{O}}\sum_{(i,j,m)\in\mathcal{A}} E[\rho]^n_{i,j,m,0}}_{\text{overdue penalty cost}}$$

variable leg transportation cost | terminal transshipment cost | overdue penalty cost

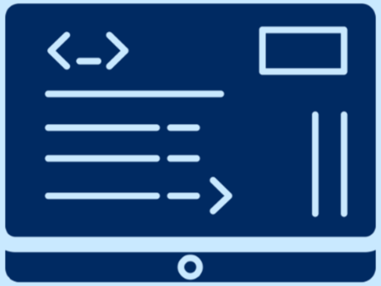
low cost (variable leg transportation cost + terminal transshipment cost)

on-time delivery (overdue penalty cost)

Methodology

Constraints

Subjected to three constraint sets.



Optimization model

- Construct optimal transportation routes
- MILP

Constraints

- Network flow constraints
- Expected cost constraints
- Expected penalty constraints

Methodology

Optimization model

Constraints

Network flow constraints

$$\sum_{(o_n,j,m)\in\mathcal{A}} x^n_{o_n,j,m,0} = 1 \qquad \forall n \in \mathcal{O}$$

$$\sum_{(i,j,m)\in\mathcal{A}} x^n_{i,j,m,0} = 1 \qquad \forall n \in \mathcal{O}$$

$$x^n_{i,j,m,t} \leq \sum_{(j,k,h)\in\mathcal{A}} x^n_{j,k,h,t+l^s_{i,j,m}} \qquad \forall n \in \mathcal{O}, \forall (i,j,m) \in \mathcal{A}, \forall t \in \mathcal{T}, \forall s \in \mathcal{S}$$

$$\sum_{(i,j,m)\in\mathcal{A}} x^n_{i,j,m,t} \leq 1 \qquad \forall n \in \mathcal{O}, \forall i \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$x^n_{d_n,d_n,storage,T} = 1 \qquad \forall n \in \mathcal{O}$$

$$\sum_{(i,j,m)\in\mathcal{A}} x^n_{i,j,m,T} = 1 \qquad \forall n \in \mathcal{O}$$

$$1 + w^n_{i,g,m,t+l^s_{k,i,g}} \geq x^n_{k,i,g,t} + x^n_{i,j,m,t+l^s_{k,i,g}} \qquad \forall (k,i,g) \in \mathcal{A}, \forall (i,j,m)\ \mathcal{A}, \forall t \in \mathcal{T}, \forall s \in \mathcal{S}$$

$$w^n_{i,storage,m,0} \geq x^n_{i,j,m,0} \qquad \forall (i,j,m) \in \mathcal{A}, i \in \mathcal{N}_o$$

$$x^n_{i,j,m,t} \in \{0,1\} \qquad \forall n \in \mathcal{O}, \forall (i,j,m) \in \mathcal{A}, \forall t \in \mathcal{T}$$

$$w^n_{i,g,m,t} \in \{0,1\} \qquad \forall n \in \mathcal{O}, \forall i \in \mathcal{N}, \forall g,m \in \mathcal{M}, \forall t \in \mathcal{T}$$

Methodology

Optimization model

Constraints

Expected cost constraints

$$E[C^V]^n_{i,j,m,t} \geq c^V_{i,j,m} f_n + \sum_s p^s_{i,j,m} \sum_{(j,k,h)\in\mathcal{A}} E[C^V]^n_{i,j,m,t+l^s_{i,j,m}} - Z(1 - x^n_{i,j,m,t})$$

$$\forall n \in \mathcal{O}, \forall (i,j,m) \in \mathcal{A}, \forall t \in \mathcal{T}$$

$$E[C^V]^n_{i,j,m,t} \geq 0 \qquad \forall n \in \mathcal{O}, \forall (i,j,m) \in \mathcal{A}, \forall t \in \mathcal{T}$$

$$E[C^T]^n_{i,g,m,t} \geq c^T_{g,m} f_n + \sum_s p^s_{i,j,m} \sum_{(j,k,h)\in\mathcal{A}} E[C^T]^n_{i,m,h,t+l^s_{i,j,m}} - Z\left(1 - w^n_{i,g,m,t}\right) - Z\left(1 - x^n_{i,j,m,t}\right)$$

$$\forall n \in \mathcal{O}, \forall (i,j,m) \in \mathcal{A}, i \in \mathcal{N}_t, \forall g \in \mathcal{M}, \forall t \in \mathcal{T}$$

$$E[C^T]^n_{i,g,m,t} \geq \sum_s p^s_{i,j,m} \sum_{(j,k,h)\in\mathcal{A}} E[C^T]^n_{i,m,h,t+l^s_{i,j,m}} - Z\left(1 - w^n_{i,g,m,t}\right) - Z\left(1 - x^n_{i,j,m,t}\right)$$

$$\forall n \in \mathcal{O}, \forall (i,j,m) \in \mathcal{A}, i \in \mathcal{N}_o, \forall g \in \mathcal{M}, \forall t \in \mathcal{T}$$

$$E[C^T]^n_{i,g,m,t} \geq 0 \qquad \forall n \in \mathcal{O}, \forall i \in \mathcal{N}, \forall g, m \in \mathcal{M}, \forall t \in \mathcal{T}$$

Methodology

Optimization model

Constraints

Expected penalty constraints

$$E[\rho]^{n}_{i,j,m,t} \geq \sum_{s} p^{s}_{i,j,m} \sum_{(j,k,h)\in\mathcal{A}} E[\rho]^{n}_{j,k,h,t+l^{s}_{i,j,m}} - Z(1-x^{n}_{i,j,m,t}) \qquad \forall n \in \mathcal{O}, \forall (i,j,m) \in \mathcal{A}, i \in \mathcal{N}_0 \cup \mathcal{N}_t, \forall t \in \mathcal{T}$$

$$E[\rho]^{n}_{i,j,m,t} \geq (t-k_n) f_n \rho - Z\left(1-x^{n}_{i,j,m,t}\right) \qquad \forall n \in \mathcal{O}, \forall (i,j,m) \in \mathcal{A}, i \in \mathcal{N}_d, \forall t \in \mathcal{T}$$

$$E[\rho]^{n}_{i,j,m,t} \geq 0 \qquad \forall n \in \mathcal{O}, \forall (i,j,m) \in \mathcal{A}, \forall t \in \mathcal{T}$$

Numerical study

Sensitivity analyses

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Numerical study – Impact of penalty cost

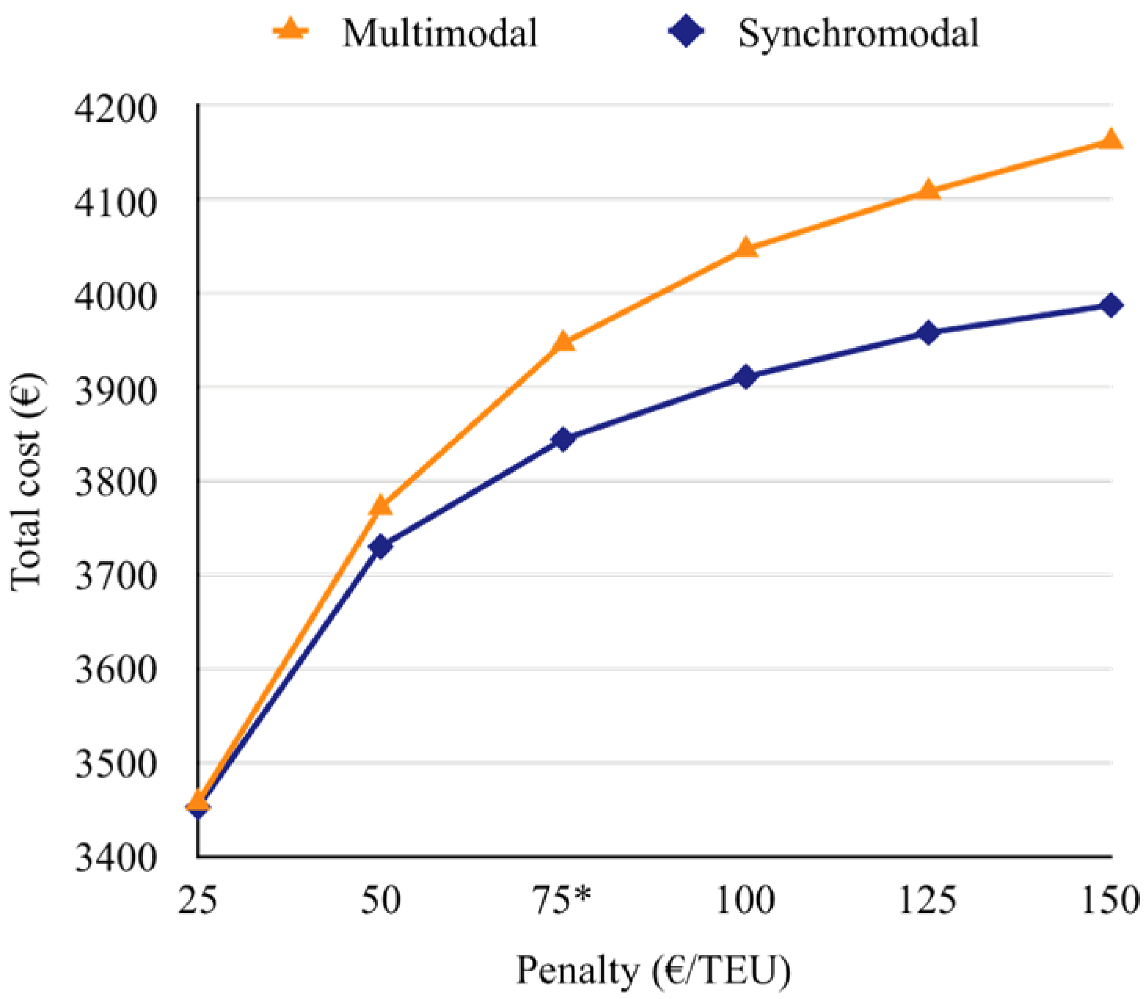
Penalty per period of late delivery

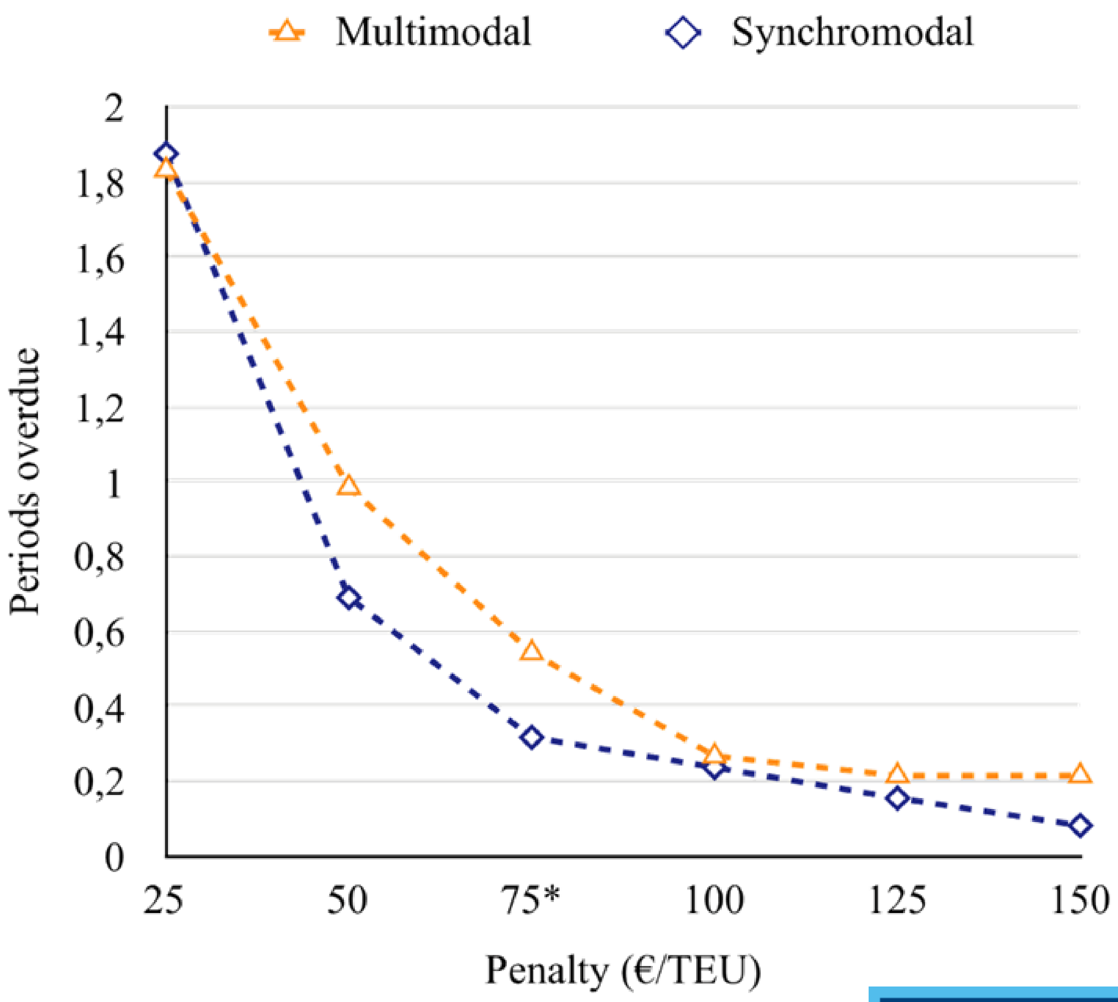
Transshipment cost in terminals

Carbon tax per ton CO_2

Reliability of transportation modes

Numerical study – Impact of penalty cost





Numerical study – Impact of transshipment cost

Penalty per period
of late delivery

Transshipment cost
in terminals

Carbon tax
per ton CO_2

Reliability of
transportation modes

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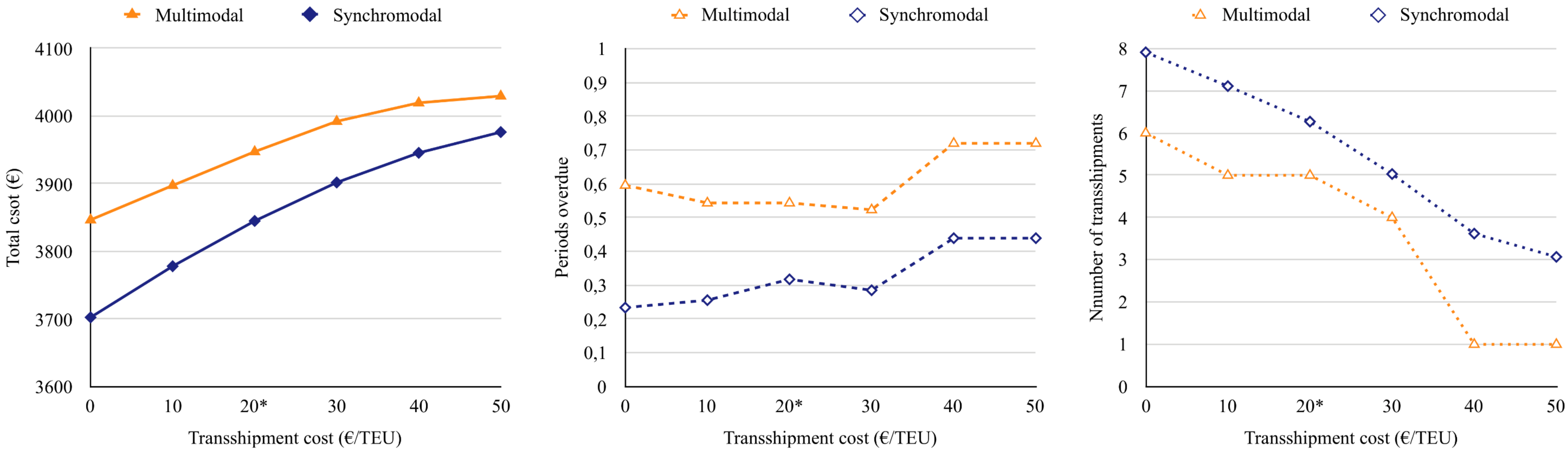
Numerical study – Impact of transshipment cost



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Numerical study – Sensitivity analyses

Penalty per period
of late delivery

Transshipment cost
in terminals

Carbon tax
per ton CO_2

Probability distribution
over scenarios

Synchromodality > Multimodality
- Cost → Relative cost reduction ↑ :
  - Penalty ↑
  - Transshipment cost ↓
- Service quality

regardless of the parameter value

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Numerical study – Impact of carbon tax

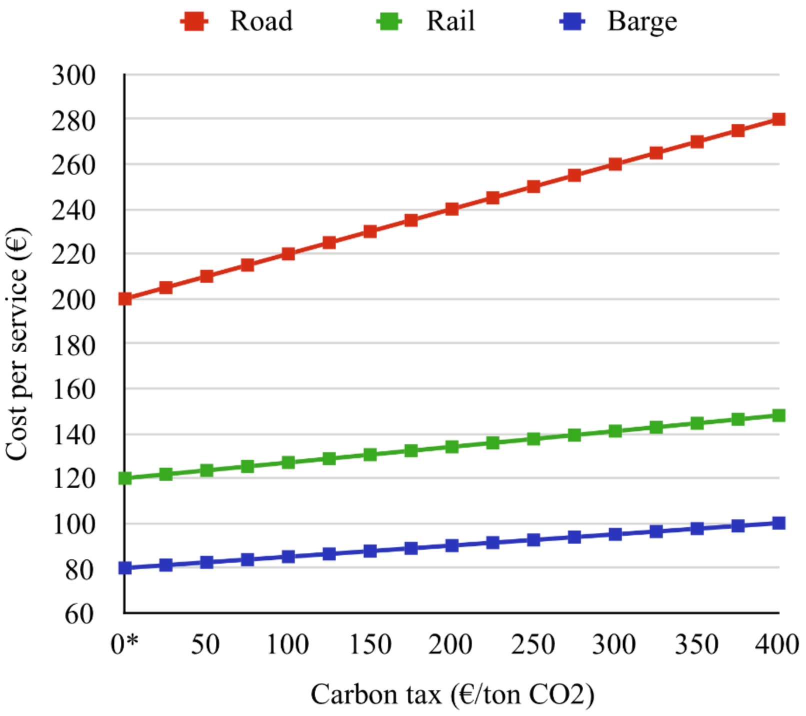
Penalty per period of late delivery

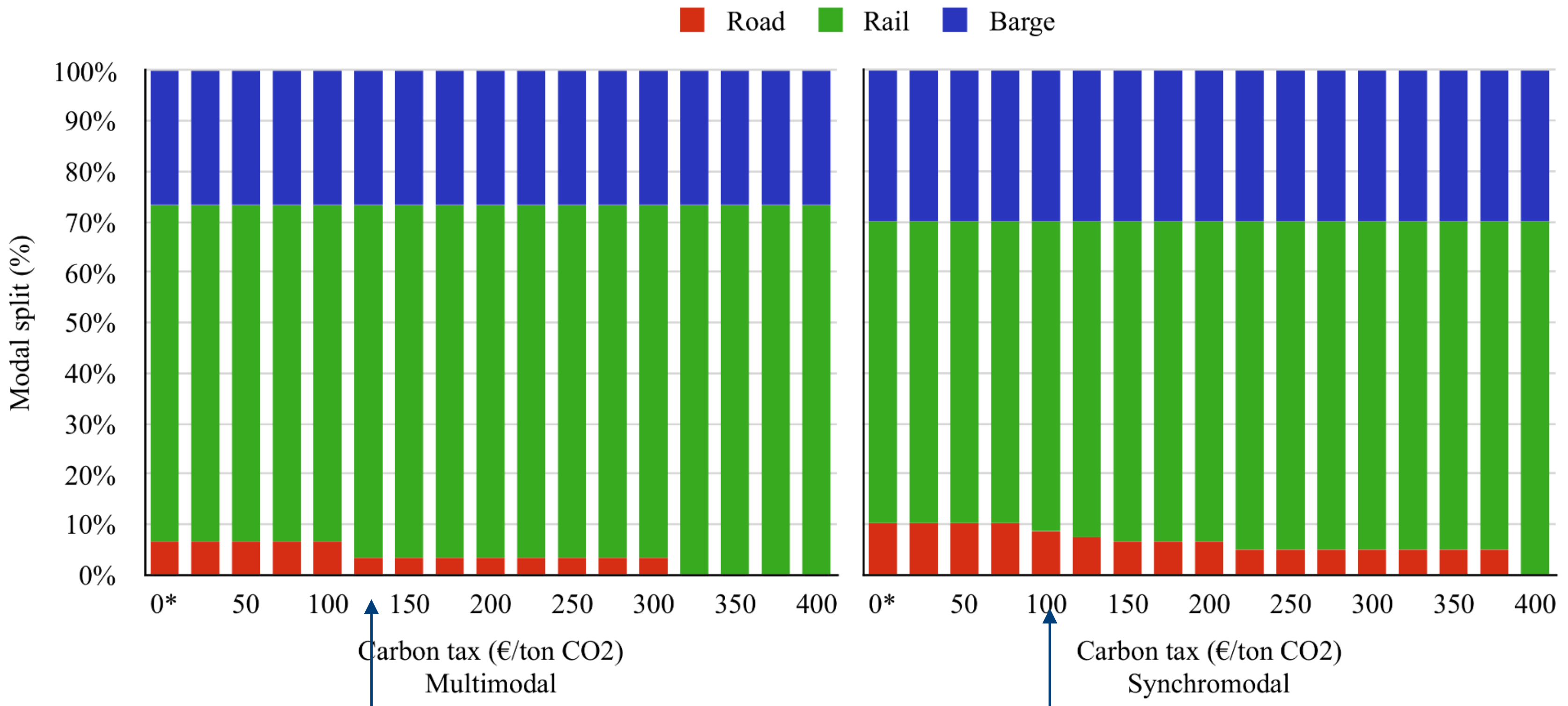
Transshipment cost in terminals

Carbon tax per ton CO_2

Reliability of transportation modes

Numerical study – Impact of carbon tax

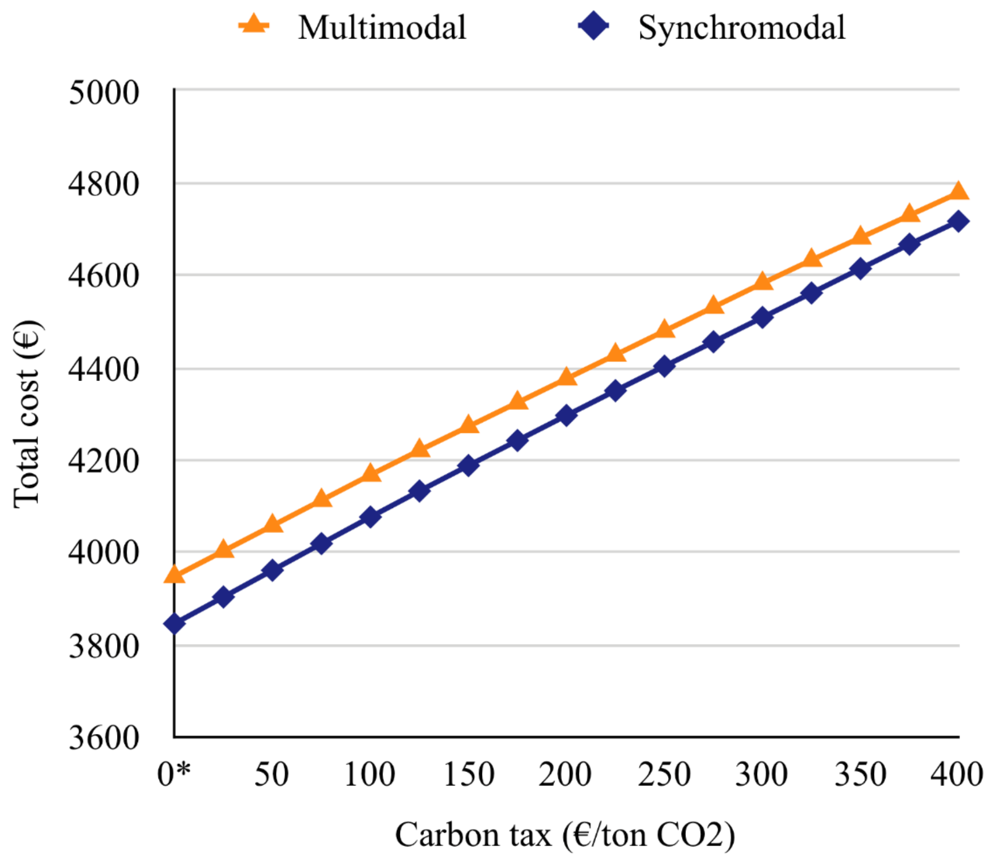


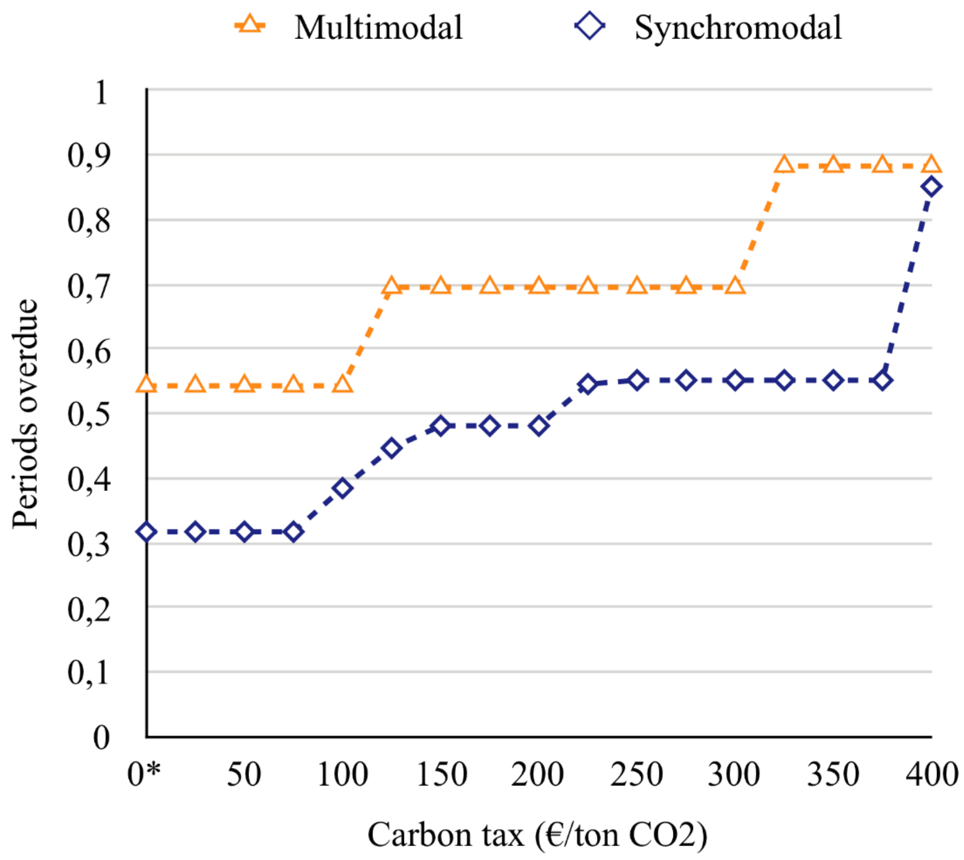


125 € / ton CO_2

100 € / ton CO_2

Numerical study – Impact of carbon tax





Numerical study – Impact of reliability

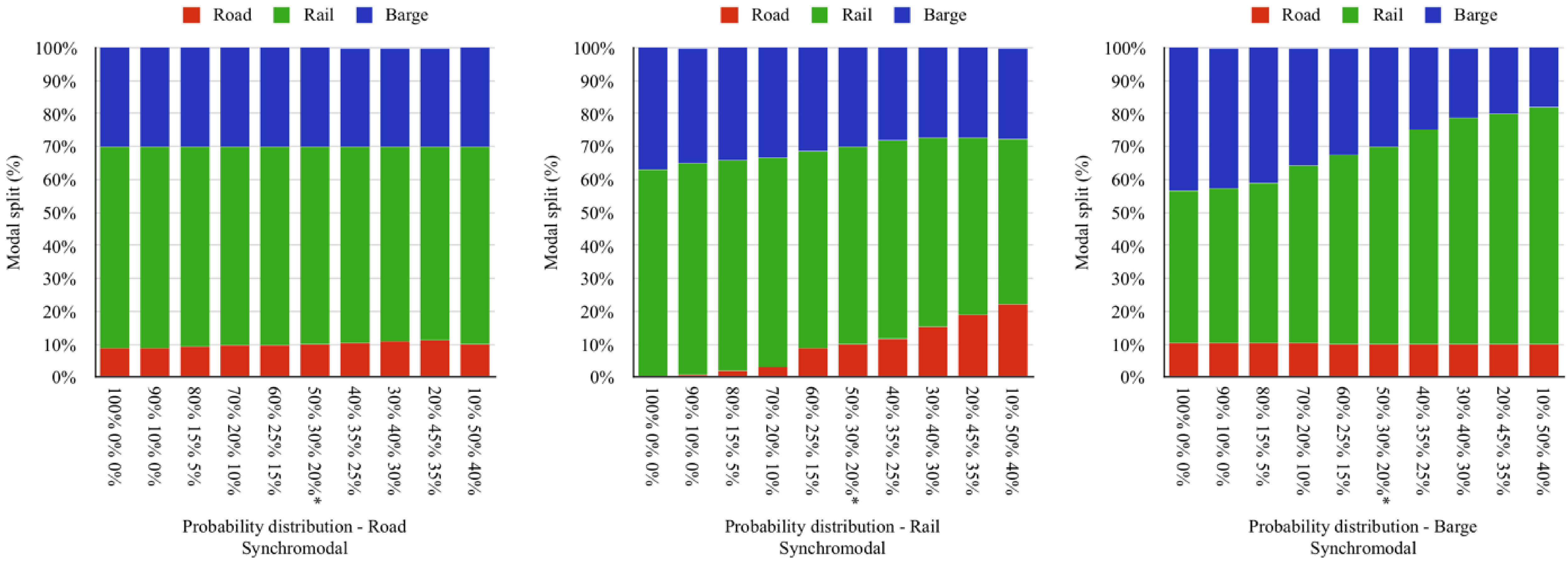
Penalty per period of late delivery

Transshipment cost in terminals

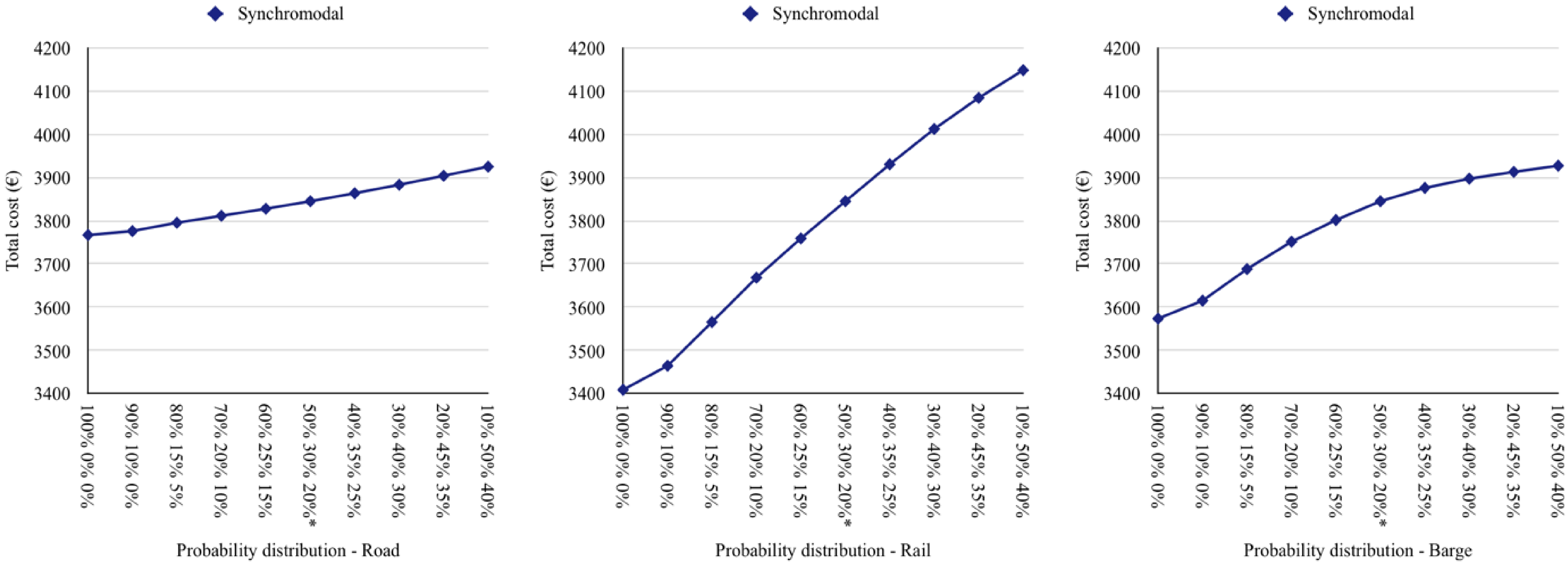
Carbon tax per ton CO_2

Reliability of transportation modes

Numerical study – Impact of reliability



Numerical study – Impact of reliability



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Numerical study – Impact of reliability