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Integrated Mode Choice and Vehicle Routing for Container Transport*

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Abstract— **It is desirable to improve the efficiency of container transport both from an economical and an environmental point of view, as increased efficiency decreases costs and emissions per transported container. Modern transport schemes, such as synchromodal transport, use a-modal bookings to increase the flexibility of the transport providers where the mode choice can be postponed until all demand for a planning period is known. We show in this paper the impact of planning the routes of containers, and thus the mode choice, together with truck routing. The developed *integrated container and truck routing model* is compared to a *two-stage model* that represents current practice, where the route of the containers are decided upon assuming an unlimited amount of trucks are always available. The two models are compared on several simulated, hinterland scenarios. In all scenarios, integrated routing performs at least as well as the two-stage model in terms of cost and the benefits of integration are more evident when there is a limited amount of trucks available. Integration of the routing increases the utilization rate of trucks and, often, a smaller truck fleet is needed. The presented model, therefore, demonstrates a proof-of-concept with promising improvements towards efficiency and environmental sustainability.**

I. INTRODUCTION

Global container transport accounted for more than 17% of the world seaborne trade in 2017 and there is a significant increase every year in the amount of containerized cargo [1]. This increase makes the efficiency of the involved transport operations more critical and different innovative concepts are being discussed as a solution. Synchromodal transport is one of those innovative concepts taking a step further from intermodal transport with a-modal bookings and real-time adaptations to the transport plans to cope with changing conditions in the system [2], [3]. When moving towards such innovative concepts, the transport operations need to be better represented in order to bring significant impacts in terms of sustainability and efficiency.

Even though sustainability is one of the main objectives in the recent years, road transport was still the leading mode of freight transport in the European Union (52.4%) followed by maritime transport (30.0%) and rail transport (13.0%) in 2018 [4]. Truck transport contributes the most to the negative monetary impact the transport sector has on environment and society [5], while trucks are reported to drive empty frequently [6]. Nevertheless, it is a common assumption in the literature that infinitely many trucks are instantly available when needed (e.g. [7], [8]). This assumption simplifies the models as the movement of the trucks does not need to be represented in detail. However, [9] shows that when the truck routes are modeled and tracked, the decisions on the network changes significantly, which questions the validity of this widely used assumption.

In the literature, container transport decisions are typically analyzed at three levels [10]: the strategic, which relates to the investment decisions on the transport infrastructure; the tactical, which deals with optimally utilizing the existing infrastructure by choosing the services and associated modes; and the operational, which contains specific routing and timing decisions. Operational models are also often referred to as those that take care of the dynamic and/or stochastic nature of the operations, as in the case of [8]. The studied synchromodal transport system in this paper takes the schedules of train and barge services as inputs, i.e., they are considered as tactical decisions, and focuses on the decisions of individual container and truck routing at the operational level. In a sense, the operational decisions are considered from the shippers' and truck operators' point of view where barge and train fees are given per container with no pre-reserved capacity.

The objective of this paper is to address the common assumption of instantly available trucks by developing the *integrated container and truck routing* model (ICTR) in the context of a synchromodal transport network. The proposed integrated model, ICTR, is computationally demanding and to show the potential of such a model as a proof-of-concept, we consider a static and deterministic case where the information on the containers to be transported is assumed to be known upfront. The integration of truck movements leads to the representation of the full routes of the trucks in the model which enables to observe and act-upon empty truck routes. Except [9], the empty truck routes are typically not accounted for in the intermodal / synchromodal transport literature as trucks appear only when needed (e.g., [8], [11], [12], [13], [7]). The literature with detailed models of truck routes focuses on vehicle routing problems as in the case of [14] where a single mode is considered. The capability of accounting for empty truck movements enables to optimize the truck routes in such a way to make use of the locations of the trucks and therefore to better utilize the resources. Note that we model container routes individually. This is different than [9] where an aggregate model is considered and the truck routes are not optimized based on individual truck routes. Therefore, the main contribution of this paper to the synchromodal transport field is the individual and integrated

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routing of container and trucks in a network that include scheduled barge and train services.

The remainder of the paper is organized as follows. Section II presents the ICTR model formulation as well as the *two-stage* benchmark *model*. The conducted simulation experiments to evaluate the added value of the integrated model are presented in Section III together with the discussion of the results. The paper is concluded and future research direction are provided in Section IV.

II. INTEGRATED CONTAINER AND TRUCK ROUTING

The proposed integrated container and truck routing (ICTR) model is developed under a number of assumptions:

- There is a central decision maker.
- The information on scheduled services is available to the decision maker (schedule, capacity limits and cost per container).
- Truck cost is given as a transport cost for the arcs traveled and a driver cost per unit time the truck is used after its operational hours start.
- (Un)loading is not considered.
- Container due dates are hard deadlines.

Given the above, the model is formulated as a mixed integer linear programming problem which is presented next. The movement of trucks is modeled in such a way that each move of the truck, i.e. each time a truck traverses an arc on the network, is considered when defining the related decision variables. In order to evaluate the performance of ICTR, a two-stage benchmark model is also developed mimicking the current practice. This model is already expected to perform better than traditional decision making, as it is based on optimization models. In its first stage, the benchmark model mimics a freight forwarder routing the containers based on the schedules of ships and trains assuming trucks will be available when needed. In the second stage, decisions represent those of a truck operator who routes the trucks to serve the container routes decided by the freight forwarder. Even if the freight forwarder and the truck operator are part of the same organization, this hierarchy of decisions is common in current practice. The notation used for the formulation is given in Table II.

A. ICTR formulation

The objective function of ICTR (1) minimizes the total costs that consists of cost of operating trucks including the driver and transport costs, cost of using scheduled services and finally the waiting cost of containers at intermediate nodes in the network.

$$\min \sum_{t\in T}\left(\tau_{d_t}^{t,m_f} e^t + \sum_{m\in\mathcal{M}}\sum_{i\in N}\sum_{j\in N} x_{ij}^{t,m} f_{ij}\right) + \sum_{k\in K}\left(\sum_{a\in A} c_a \bar{z}_a^k + \sum_{i\in N} w_i^k b_i\right) \quad (1)$$

TABLE I

NOTATION

Indices and sets	
$t \in T$	trucks
$m \in \mathcal{M}$	moves of a truck
$i, j \in N$	nodes in the network
$a \in A$	scheduled services
$k \in K$	containers
Parameters	
b_i	waiting cost of a container at node i
$(\bar{o}_k, \bar{d}_k)$	origin-destination of container k
$(\bar{r}_k, \bar{q}_k)$	the release time and due date of container k
f_{ij}	transport cost of a truck on arc (i, j)
e^t	driver costs of truck t
(o_t, d_t)	origin-destination of truck t
(r_t, q_t)	operational hours of truck t
m_0, m_f	move 0 and final move
σ_{ij}	road travel time on arc (i, j)
l_a	departure time for scheduled service a
v_a	travel time for service a
(s_a, t_a)	origin-destination of service a
u_a	container capacity of service a
c_a	the cost of transporting a container by service a
M	a sufficiently large positive number
Decision variables	
$\bar{z}_a^k$	binary, 1 if container k uses service a
z_{ij}^k	binary, 1 if container k travels arc (i, j) by a truck
$x_{ij}^{t,m}$	binary, 1 if truck t travels arc (i, j) in move m
$y_{ij}^{k,t,m}$	binary, 1 if truck t in move m transports container k
ρ_i^k	arrival time of container k at node i
ξ_i^k	departure time of container k from node i
$\tau_i^{t,m}$	arrival time of truck t at node i in move m
ϕ^t	departure time of truck t from the origin
w_i^k	waiting time of container k at an intermediate node i

We group the constraints in different parts. First we have constraints (2)-(7) on container routing. They make sure that containers are consistently transported through the network by trucks and/or scheduled services, their flow is conserved, they do not make loops and the capacity of services is not violated.

$$\sum_{i\in N} z_{\bar{o}_k,i}^k + \sum_{a\in A: s_a=\bar{o}_k} \bar{z}_a^k = 1 \quad \forall k \in K \quad (2)$$

$$\sum_{i\in N} z_{i,\bar{d}_k}^k + \sum_{a\in A: t_a=\bar{d}_k} \bar{z}_a^k = 1 \quad \forall k \in K \quad (3)$$

$$\sum_{j\in N} z_{ji}^k + \sum_{a\in A: t_a=i} \bar{z}_a^k = \sum_{j\in N} z_{ij}^k + \sum_{a\in A: s_a=i} \bar{z}_a^k \qquad \forall k \in K,\ i \in N \setminus \{\bar{o}_k, \bar{d}_k\} \quad (4)$$

$$\sum_{a\in A: t_a=i} \bar{z}_a^k + \sum_{j\in N} z_{ji}^k \le 1 \quad \forall k \in K, i \in N \quad (5)$$

$$\sum_{a\in A:(t_a=i \& s_a=j)} \bar{z}_a^k + \sum_{a\in A:(t_a=j \& s_a=i)} \bar{z}_a^k + z_{ij}^k + z_{ji}^k \le 1 \quad \forall k \in K, i, j \in N \quad (6)$$

$$\sum_{k\in K} \bar{z}_a^k \le u_a \quad \forall a \in A \quad (7)$$

Constraints (8)-(10) enable a consistent truck routing. First, each truck can only start at its depot. Next, if a truck leaves the depot as its first move, it needs to go back to the depot as the last move and it can only traverse one arc in each move (9). Finally, the flow conservation is maintained by (10). Note that, the number of truck moves should be adjusted in each implementation of ICTR to reflect the size of the network, travel times and operation hours of the trucks.

$$\sum_{i\in N} x_{o_t,i}^{t,m_0} = \sum_{i\in N}\sum_{j\in N} x_{ij}^{t,m_0} \tag{8}$$

$$\sum_{i\in N} x_{o_t,i}^{t,m_0} = \sum_{i\in N} x_{i,\bar{d}_k}^{t,m_f} \leq 1 \quad \forall t \in T \tag{9}$$

$$\sum_{j\in N} x_{ji}^{t,m} = \sum_{j\in N} x_{ij}^{t,m+1} \forall t \in T,\, m \in \mathcal{M} \setminus \{m_f\},\, i \in N \tag{10}$$

Constraints (11) and (12) couple the decision variables on container and truck routing such that, a container can be assigned to a truck in a move on an arc only if that truck is traveling on that arc in that move. Moreover, the decision on whether the container transported over the road is set according to its assignment to a specific truck.

$$x_{ij}^{t,m} \geq \sum_{k\in K} y_{ij}^{k,t,m} \forall t \in T,\, m \in \mathcal{M},\, i,j \in N \tag{11}$$

$$z_{ij}^{k} = \sum_{t\in T}\sum_{m\in\mathcal{M}} y_{ij}^{k,t,m} \;\forall k \in K,\, i,j \in N \tag{12}$$

Time consistency of the trucks in the network is maintained by constraints (13)-(16). The arrival time of a truck at two consecutive nodes is ensured to be consistent with the needed travel time in between by (13) and (14). The departure from the depot and arrival back to the depot in the last move is allowed to only happen within the operation hours of the truck by (15) and (16).

$$\tau_j^{t,m} \geq \tau_i^{t,m-1} + \sigma_{ij} x_{ij}^{t,m} \qquad \forall i,j \in N,\, t \in T,\, m \in M \setminus m_0 \tag{13}$$

$$\tau_j^{t,m_0} \geq \phi^t + \sigma_{ij} x_{ij}^{t,m_0} \;\; \forall i,j \in N,\, t \in T \tag{14}$$

$$\phi^t \geq r_t \quad \forall t \in T \tag{15}$$

$$\tau_{d_t}^{t,m_f} \leq q_t \quad \forall t \in T \tag{16}$$

Next, we have the time constraints for containers. The arrival time of a container at a node is maintained to be consistent with the mode (truck or scheduled service) that is transported by thanks to constraints (17)-(21). Similarly, the departure time is also aligned with the assigned mode by constraints (22)-(26). Waiting time of a container at a node is given by (27) and (28). Finally, the release time and due date of a container is respected by constraints (29)-(30).

$$\rho_i^k \geq \tau_i^{t,m} - M(1 - y_{ji}^{k,t,m}) \qquad \forall k \in K,\, t \in T,\, m \in \mathcal{M},\, i,j \in N \tag{17}$$

$$\rho_i^k \leq \tau_i^{t,m} + M(1 - y_{ji}^{k,t,m}) \qquad \forall k \in K,\, t \in T,\, m \in \mathcal{M},\, i,j \in N \tag{18}$$

$$\rho_i^k \geq l_a + v_a - M(1 - \bar{z}_a^k) \qquad \forall k \in K,\, i \in N,\, a \in A : t_a = i \tag{19}$$

$$\rho_i^k \leq l_a + v_a + M(1 - \bar{z}_a^k) \qquad \forall k \in K,\, i \in N,\, a \in A : t_a = i \tag{20}$$

$$\rho_i^k \leq l_a + M(1 - \bar{z}_a^k) \qquad \forall k \in K, i \in N, a \in A : s_a = i \tag{21}$$

$$\xi_i^k \geq \tau_i^{t,m-1} - M(1 - y_{ij}^{k,t,m}) \qquad \forall k \in K, t \in T, m \in \mathcal{M} \setminus \{m_0\}, i,j \in N \tag{22}$$

$$\xi_i^k \geq \tau_j^{t,m} - \sigma_{ij} - M(1 - y_{ij}^{k,t,m}) \qquad \forall k \in K,\, t \in T,\, m \in \mathcal{M},\, i,j \in N \tag{23}$$

$$\xi_i^k \leq \tau_j^{t,m} - \sigma_{ij} + M(1 - y_{ij}^{k,t,m}) \qquad \forall k \in K,\, t \in T,\, m \in \mathcal{M},\, i,j \in N \tag{24}$$

$$\xi_i^k \geq l_a \bar{z}_a^k \quad \forall k \in K,\, i \in N,\, a \in A : t_a = i \tag{25}$$

$$\xi_i^k \leq l_a + M(1 - \bar{z}_a^k) \qquad \forall k \in K,\, i \in N,\, a \in A : t_a = i \tag{26}$$

$$\xi_i^k = w_i^k + \rho_i^k \quad \forall i \in N,\, k \in K \tag{27}$$

$$w_i^k \geq 0 \quad \forall i \in N,\, k \in K \tag{28}$$

$$\xi_{\bar{o}_k}^k \geq \bar{r}_k \quad \forall k \in K \tag{29}$$

$$\rho_{\bar{d}_k}^k \leq \bar{q}_k \quad \forall k \in K \tag{30}$$

Finally, binary variable definitions are given by (31)-(34).

$$\bar{z}_a^k \in \{0,1\} \quad \forall k \in K,\, a \in A \tag{31}$$

$$z_{ij}^k \in \{0,1\} \quad \forall k \in K,\, i,j \in N \tag{32}$$

$$x_{ij}^{t,m} \in \{0,1\} \quad \forall t \in T,\, m \in \mathcal{M},\, i,j \in N \tag{33}$$

$$y_{ij}^{k,t,m} \in \{0,1\} \quad \forall k \in K,\, t \in T,\, m \in \mathcal{M},\, i,j \in N \tag{34}$$

B. Benchmark: Two-Stage Model

In order to assess the benefits of the proposed integrated model, a benchmark model that represents the current practice was developed. Under the same assumptions of ICTR, this benchmark model consists of two stages. First, the containers are routed without considering the needed truck routing. This stage can be considered as the decision mechanism of a freight forwarder who afterwards needs to ask service from a truck operator. The second stage takes the decisions of ICTR that are not covered by the first stage. The second stage is thus associated with the truck routing decisions to fulfill the container demand and can be considered as the decision of a truck operator.

1) Stage 1: Container routing: The objective of this stage is the minimization of the costs associated with scheduled services, waiting time of containers and the transport costs of trucks as given by (36). The container routing constraints given by (2)-(7) for ICTR are also valid for this stage. However, truck routing constraints given by (8)-(10), the coupling constraints (11)-(12) and the time constraints for trucks (13)-(16) are not used here by definition. When it comes to the time constraints of containers, (19)-(21) and (25)-(30) are still valid and the only part that needs to be adapted is the relation to time of the trucks. Therefore, constraints (17)-(18) and (22)-(24) are not needed and instead the following is introduced to ensure the traveling time of containers on roads is consistent with the needed travel time:

$$\rho_i^k \geq \sigma_{i,j} + \xi_i^k - M(1 - z_{ij}^k) \; \forall k \in K, i,j \in N \tag{35}$$

Based on the above, the full model for Stage 1 is given as follows:

$$\min \sum_{k \in K} \left(\sum_{a \in A} c_a \bar{z}_a^k + \sum_{i \in N} w_i^k b_i + \sum_{i \in N} \sum_{j \in N} z_{ij}^k f_{ij} \right) \tag{36}$$

$$\text{s.t.}(2) - (7), (19) - (21), (25) - (32), (35). \tag{37}$$

2) Stage 2: Truck routing: The objective of the second stage is the same as ICTR (1) and therefore can be compared with ICTR when analyzing the results. Similarly, all the constraints of ICTR are also valid here. Nevertheless, the container routing decisions, namely the z and $\bar{z}$ decision variables, are now input parameters. Therefore, in a sense the container routing constraints (2)-(7) are already maintained as all the involved decision variables are fixed.

III. SIMULATION EXPERIMENTS

To show the impact of integrating the planning of individual containers' and trucks' routes through a synchromodal transport network, ICTR was compared to the two-stage model with simulation experiments for one day and 10 hours of transport. Since the aim of this paper is to demonstrate ICTR as a proof of concept, we did not focus on developing customized solution methods. We employed MATLAB with standard optimization using Yalmip [15] and Gurobi for implementation. To decrease computation time, the solution of the two-stage model was used to warmstart ICTR when possible.

ICTR and the two-stage model were compared for seven different scenarios on the network shown in Figure 1. The figure indicates the distance, $\gamma_{ij} = \gamma_{ji}$ and travel time, $\sigma_{ij} = \sigma_{ji}$, for all roads. In all scenarios, the transport cost of a truck is considered as f_{ij} =€$0.344 \times \gamma_{ij}$ and the cost of the truck drivers' time is e^t =€0.05 per min for every truck t. Waiting containers cost b_i =€0.0005 per min at all nodes i. The cost of transporting one container by a scheduled service is c_a =€45 for trains and c_a =€4.3 for ships.

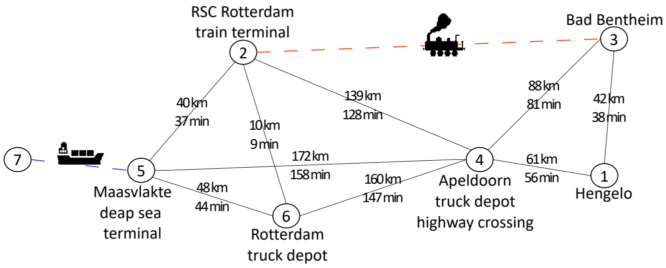

Fig. 1. Network used in the simulation experiments.

In the base scenario, six containers have to be transported. It is a realistic scenario as it has slightly more import than export and a sufficient number of trucks available. They are all released at the beginning of the simulation, $\bar{r}_k = 1 \; \forall \, k \in \{1, ..., 6\}$, and have due dates 2000 min after, $\bar{q}_k = 2000 \; \forall \, k \in \{1, ..., 6\}$. Their origins and destinations are seen in Table II. Five trucks are available: three that start and end in Rotterdam and two in Apeldoorn. They are all available 2000 min from the beginning of the simulation, $r_t = 1$, $q_t = 2000 \; \forall t \in \{1, ..., 5\}$. For each truck, the maximum number of moves, m_f, is defined as six. Figure 2 shows the schedules for the train and ship. The capacities of the scheduled services are not limiting factors.

TABLE II
TRANSPORT DEMAND.

Base	Import	Import& Export	Increased	Tight time	
$\bar{o}_1 = 7$	$\bar{o}_1 = 7$	$\bar{o}_1 = 7$	$\bar{o}_7 = 7$	$\bar{o}_1 = 7$	$\bar{r}_1 = 5$
$\bar{d}_1 = 3$	$\bar{d}_1 = 1$	$\bar{d}_1 = 1$	$\bar{d}_7 = 1$	$\bar{d}_1 = 3$	$\bar{q}_1 = 1070$
$\bar{o}_2 = 7$	$\bar{o}_2 = 7$	$\bar{o}_2 = 7$	$\bar{o}_8 = 1$	$\bar{o}_2 = 7$	$\bar{r}_2 = 5$
$\bar{d}_2 = 3$	$\bar{d}_2 = 1$	$\bar{d}_2 = 1$	$\bar{d}_8 = 7$	$\bar{d}_2 = 3$	$\bar{q}_2 = 1070$
$\bar{o}_3 = 7$	$\bar{o}_3 = 7$	$\bar{o}_3 = 7$	$\bar{o}_9 = 3$	$\bar{o}_3 = 7$	$\bar{r}_3 = 5$
$\bar{d}_3 = 1$	$\bar{d}_3 = 1$	$\bar{d}_3 = 1$	$\bar{d}_9 = 7$	$\bar{d}_3 = 1$	$\bar{q}_3 = 1000$
$\bar{o}_4 = 7$	$\bar{o}_4 = 7$	$\bar{o}_4 = 1$	$\bar{o}_{10} = 3$	$\bar{o}_4 = 7$	$\bar{r}_4 = 5$
$\bar{d}_4 = 1$	$\bar{d}_4 = 1$	$\bar{d}_4 = 7$	$\bar{d}_{10} = 7$	$\bar{d}_4 = 1$	$\bar{q}_4 = 1120$
$\bar{o}_5 = 3$	$\bar{o}_5 = 7$	$\bar{o}_5 = 1$		$\bar{o}_5 = 3$	$\bar{r}_5 = 60$
$\bar{d}_5 = 1$	$\bar{d}_5 = 1$	$\bar{d}_5 = 7$		$\bar{d}_5 = 1$	$\bar{q}_5 = 120$
$\bar{o}_6 = 3$	$\bar{o}_6 = 7$	$\bar{o}_6 = 1$		$\bar{o}_6 = 3$	$\bar{r}_6 = 160$
$\bar{d}_6 = 7$	$\bar{d}_6 = 1$	$\bar{d}_6 = 7$		$\bar{d}_6 = 7$	$\bar{q}_6 = 2000$

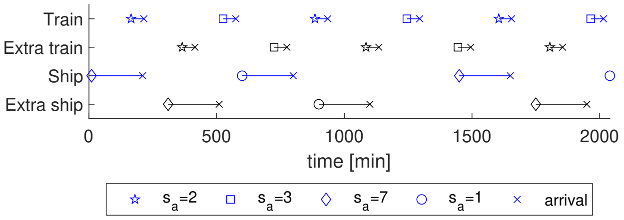

Fig. 2. Schedule of the train and ship. The extra train and ship are only used in the scheduled services scenario.

In each of the remaining six scenarios, one parameter is altered. These scenarios represent different transport networks that may be applicable in real life and help to evaluate the general impact of the proposed mode. Table II gives an overview of the changes in container demand. The additional differences to the base scenario are as follows:

Single truck A single truck with 20 moves is available from Apeldoorn: $T = \{1\}$, $o_1 = d_1 = 6$, $r_1 = 1$, $q_1 = 2000$.

Import Six import containers are to be transported (no export containers).

Import & export Three import and three export containers are to be transported.

Increased The four extra containers are to be transported besides the base demand. One extra truck is available from Apeldoorn.

Tight time The containers have tighter time windows.

Scheduled services Additional scheduled services depart, see Figure 2.

A. Results and Discussion

The impact of integrating the routing of container and truck can be seen in Table III for the different scenarios. In all experiments, ICTR performs at least as well as the two-stage model in terms of cost, often with 15% to 25%

TABLE III

SIMULATION RESULTS. * FOR THE SINGLE TRUCK SCENARIO, TRUCK MOVES ARE REPORTED.

Scenario	Model	Cost (€)	Change using ICTR	Containers using train	Total truck travel (km)	Change using ICTR	Truck utilization	Number of trucks used	Total time parked (min)	Change using ICTR	CO2 emission (tonne)	Change using ICTR	Computation time (s)	Optimality gap
Base	ICTR	633	-17%	3	1086	-8%	64%	3	1159	-44%	3.13	-9%	7200	9%
	Two-stage	765		4	1175		46%	4	2058		3.45		310	0%
Single truck	ICTR	578	-16%	3	1050	-7%	66%	16*	194	-79%	3.06	-9%	7200	2%
	Two-stage	688		4	1126		48%	18*	920		3.36		52	0%
Import	ICTR	984	NA	4	1642	NA	48%	5	2735	NA	4.46	NA	7200	12%
	Two-stage	NA		6	NA		NA	NA	NA		NA		Infeasible	
Import & export	ICTR	851	-22%	2	1753	-11%	63%	4	984	-70%	4.36	-11%	7200	39%
	Two-stage	1094		3	1967		48%	5	3308		4.92		601	0%
Increased	ICTR	1276	-15%	4	2579	-7%	59%	6	998	-68%	6.60	-7%	7200	38%
	Two-stage	1499		5	2762		50%	6	3098		7.10		1080	0%
Tight time	ICTR	640	0%	3	1086	0%	64%	4	1184	0%	3.13	0%	7200	9%
	Two-stage	640		3	1086		64%	4	1184		3.13		53	0%
Scheduled services	ICTR	615	-25%	3	1068	+30%	65%	3	817	-84%	3.09	+5%	7200	5%
	Two-stage	817		5	822		40%	4	4993		2.93		54	0%

improvement. ICTR transports more containers by truck and do so in most scenarios without increasing the distance the trucks are driving. This, together with the decreased number of containers traveling by train, results in lower overall costs. As ICTR in this paper was developed with the objective of minimizing the costs with a full control on the truck routes, this is something expected. If the interests of the train operator were included in the optimization problem, i.e. considering the cost of driving empty slots on the train and the departure time decisions, the overall cost and the optimal routing would be different. It is expected that such considerations would increase the utilization of the train. With the current assumptions, integrated routing causes the train utilization to decrease in most scenarios. The total utilization of the ship does not differ between ICTR and the two-stage model since all containers with origin or destination abroad, $\bar{o}_k = 7$ or $\bar{d}_k = 7$, need to be transported by ship and the waiting cost of containers in the harbour is a negligible part of the total cost (less than €3.14 in all scenarios).

Since ICTR transport more containers without increasing the distance driven, it reaches a significantly higher truck utilization (the ratio of loaded truck distance and total truck distance). Furthermore, ICTR smooths out the demand for truck capacity and less trucks were needed in half the experiments. This is observed even in the scenario with additional scheduled services, in which the trucks drive a longer distance under ICTR than the two-stage model. When less trucks are needed, the truck operator needs to maintain a smaller truck fleet. In terms of time, the trucks are also better used when routing is integrated. In both models, the time a truck starts operating is assumed to have been agreed with the driver before the routes are planned while the end time is flexible. Since the two-stage model does not consider operation hours in the first stage, the truck return time is often later than the case when ICTR is used. This results in more parking time, where the trucks are either idle at the depot or waiting at other locations.

The importance of considering the truck routes is emphasised in the scenario with import only. Here the two-stage model needs more trucks than what are available to fulfill the transport demand leading to an infeasible solution because all containers are scheduled for the same train departure and there is not enough time for the trucks to perform multiple return trips. ICTR is able to find a feasible solution. This shows that routing containers without considering trucks can lead to infeasible plans when trucks are not plentiful, even in cases where a feasible plan actually exists. When the number of trucks is sufficient and a very specific plan has to be followed to satisfy the demand in time, the gain of using ICTR is not evident. This occurs in the scenario with tight time windows. ICTR will, however, never perform worse than the two-stage model as its objective function contains all elements of both stages' objective.

ICTR integrates the decisions from both stages of the two-stage model and has thus a larger number of decision variables. This increases the computation time. In this paper we use a publicly available optimization solver to provide a proof-of-concept without using customized pre-processing or heuristics. The results reported for ICTR are, therefore, the best known solution after 2 hours of computation after warm-starting with the solution of the two-stage model. The solver's estimated optimality gap (between the proven lower and upper bounds) is stated in Table III to indicate how far the optimizations were progressed when terminated. The two-stage model is solved or declared infeasible within 18 min. The improved cost and truck utilization achieved by ICTR thus comes at the cost of additional computation time.

However, in hard cases where trucks are scarce, the extra computation time gives significant improvements and opens up opportunities that otherwise may be infeasible.

One goal of synchromodal transport is to reduce the sector's environmental impacts. Therefore, the CO2 emissions are estimated using the method described in [16] and presented in Table III based on the results of the different experiments. In more than half the cases, there is a decrease in CO2 emissions that seems primarily to be linked to the decreased distance driven by trucks. The scenario with extra scheduled services is the only scenario with an increase in the trucks travel distance and the only one with increased CO2 emissions. It is here important to notice that the CO2 emissions are computed per container transported with the scheduled services. In the given estimates, transporting a larger share of the containers by road will cause CO2 reductions if the truck travel distance remain the same or decreases. Synchromodal transport literature often advocate for a modal share in favour of water and rail, while our results show that, if the empty slots on the scheduled services are utilized by other demand, the integration of routing decisions between different operators may be equally important from an environmental point of view.

IV. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The presented results show that when the routing of containers and trucks are integrated, the cost of transport decreases and the truck fleet is better utilized in most scenarios. Furthermore, this integration enables operating using a smaller truck fleet since the flexibility in the routing of containers can decrease the peaks in demand for truck capacity. The developed *integrated container and truck routing* (ICTR) model demonstrates that despite the increased computation time, the results of integrated planning are superior to current practice. Current practise is, in this paper, represented by the *two-stage model*, which optimizes container routes before truck routes, mimicking the hierarchy of decisions taken by different actors. Since the two-stage model is optimization-based, we expect that when compared to traditional decision making the benefits of integrating container and truck decisions will be even more pronounced.

Integration of container and truck routing brings clear improvements when only considering the shippers' and truck operators' perspective. To describe the impact on all stakeholders, more perspectives have to be reflected in the optimization problem. Therefore, future research should extend the model to include decisions regarding the scheduled services and handling capacity in terminals. Applying integrated models to scenarios of a realistic size is also an important line of future research. For this to be computationally feasible, pre-processing techniques and heuristics have to be developed for the problem. Since ICTR contains many elements from traditional vehicle routing problems, existing heuristics from this field may be applicable. Integration of decisions can, furthermore, only happen in practice if several stakeholders cooperate. ICTR requires full integration of information and responsibility, which may not be desirable for all stakeholders. Future research into distributing the decisions of ICTR is thus relevant.

The developed two-stage benchmark model mimics the current distribution of information and autonomy between a freight forwarder who decides on container routes and books capacity and a truck operator who fulfills the truck capacity requests. ICTR and the presented results can thus motivate transport stakeholders to cooperate on routing as it demonstrates a proof-of-concept for the promising improvements towards efficiency and sustainability in transport operations.

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