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Improving the vehicle utilization in freight transport

J.M. Sprokkereef

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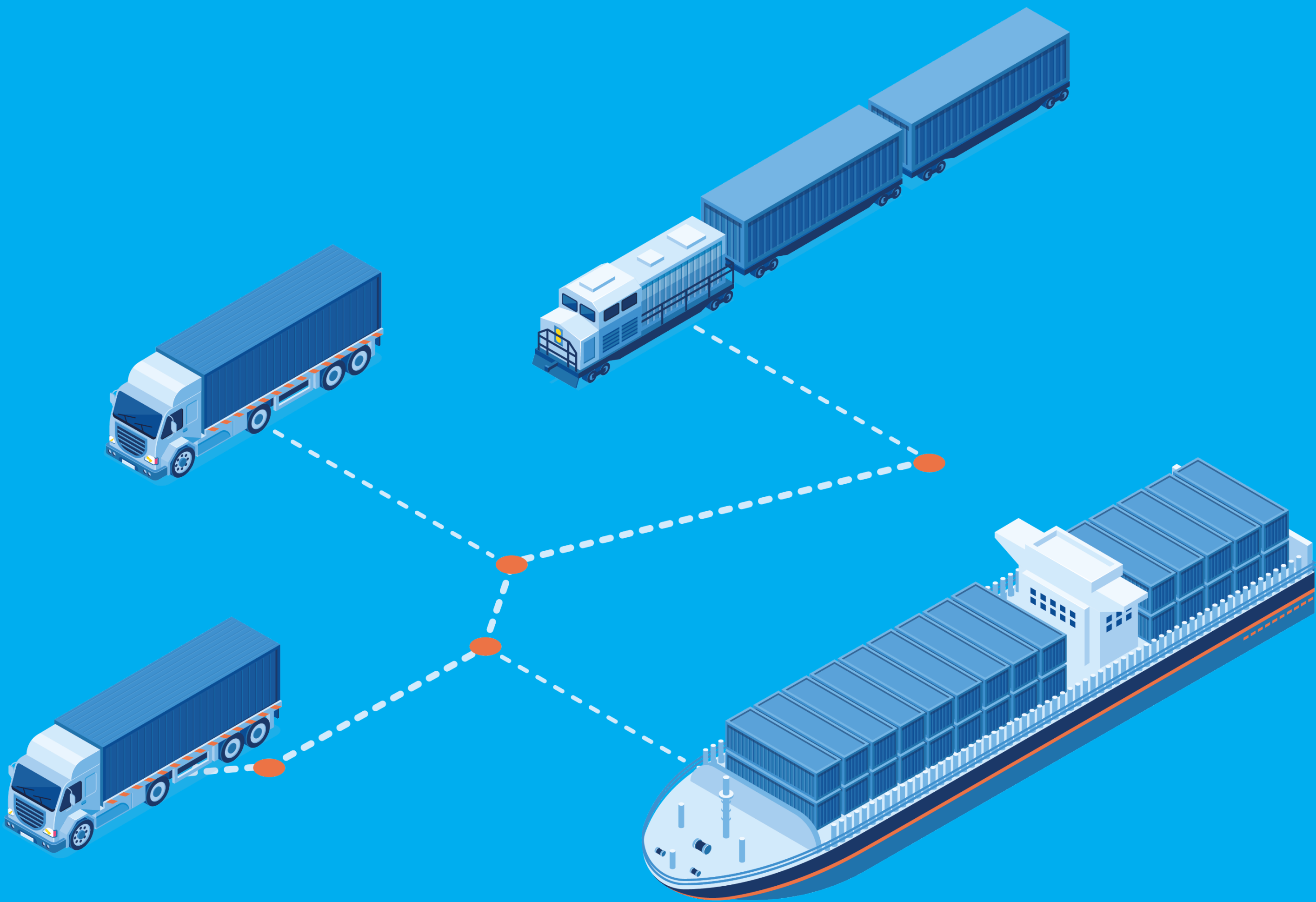

Joint optimization of container and truck routes for a synchromodal transport network

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by

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Preface

Dear reader,

In recent years the global container transport has increased significantly. Container transport is essential to keep the society running. Finding the optimal route for containers decreases the total costs and emissions of the network. I hope to sharpen the expectations about the potential of the joint optimization of both containers and trucks and to contribute to a more integrated container network.

With the opportunity to dive into one topic for several months, I found the topic of synchromodal transport an interesting topic with incredible potential. The process of modeling was for me like solving a puzzle and a lot of fun to do so. I am very grateful for all the time, feedback, and discussions with my daily supervisors Bilge and Rie. I feel that I could not have accomplished the goals I had for this research without you. The knowledge of the topic and the way you both give feedback has brought the research to a whole new level. Thank you for your continuous support throughout the process.

I would like to end by giving a special word op appreciation to my parents Ronald and Renate for their continued support throughout all study years, my girlfriend Margot for her advice and support, and all of the friends with whom I could always exchange ideas and thoughts.

Enjoy!

J.M. Sprokkereef
Delft, December 2020

Summary

Global container transport has increased significantly in the last decades, which results in an increase in container throughput [36]. Containers travel through the hinterland by truck, ship, or train. Existing models determine the route of a container through a synchromodal transport network assuming that trucks are always available. Once the container route is determined, the truck companies determine what the best truck routes are. The aim of this research is to investigate the impact of combining truck and container routing through a synchromodal network.

To find out what the impact of combining truck and container routing is, first the existing transport models are explored. Secondly, the key performance indicators are identified. Thirdly, to study this, I create the Integrated Container and Truck (ICTR) model, which can route both containers and trucks through a synchromodal network in an optimal way, considering costs, distance, and times. The model decides how the containers travel (by truck, or by a combination with ship and/or train) and the route of the trucks (when the trucks are full and when the trucks are empty). Followed by developing a benchmark model that both represents current practice well and provides information on the routes of the trucks (both when empty and full), by considering which scenarios that can be used to show what impact the integrated routing of containers and trucks can be. Finally, the results of the experiments conducted with ICTR and the benchmark are discussed in terms of total costs, CO_2 emissions, modal split and the amount of empty truck kilometers.

The existing models considering intermodal or synchromodal container transport, assume that there are unlimited trucks available at any time. In reality, trucks have to depart and return to depots, drive to a pickup point and a delivery point, etc. The most relevant papers for this research are first [26] which states that considering empty truck trips has a significant influence on the performance of the model, it considers the empty moves of a truck but does not route the truck and the container individually so time windows are not included. Secondly, the paper of [5] uses a static model which chooses the modes in a static and deterministic way, it does not route the truck and it does not consider trains. Finally, the paper of [51] who created a multi-trip multi-depot vehicle routing problem with time windows and release dates. This enables trucks to go through a network but it does not include other modes or container routing.

The key performance indicators in synchromodal transport are transport costs, CO_2 emissions, time costs, and waiting time costs. This research does in contrast to other models focus on the full trip of the truck considering loaded and empty kilometers. This is only possible because the models in this thesis consider the empty kilometers as well.

To analyse the advantages of integrating the truck route and the container route in a synchromodal network, the ICTR model and benchmark model are created. The models are static and deterministic, and has the inputs of the network, trucks, containers and scheduled services. These are models both of which individually route containers and trucks through the network. The objective is to decrease the costs, considering the route of the truck (time costs and distance costs) and the route of the container (considering the mode choice costs and the waiting time at nodes). The ICTR model integrates the routing of the trucks and the containers. The benchmark has the same constraints but is divided into two stages, since this is how transport typically is planned in practice. Stage 1 determines the route of the containers, assuming that at all nodes there are unlimited trucks available at any time. Stage 2 has to find the optimal truck route with the available trucks, based on the routes of the containers determined in Stage 1. The output of the benchmark is a feasible solution for the ICTR model, which can be used as a warm start for the ICTR to decrease the calculation time.

Simulated experiments show that there can be up to 25 % cost reduction when using integrated planning (ICTR) compared to the benchmark. Furthermore, the simulated experiment shows up to 11 % improvement in the CO_2 emissions, without including the emissions in the objective function. The improvement of using the ICTR model depends on the availability of the trucks for the containers at the nodes. This is firstly determined by the starting and final location of the truck (the distance from the depot to the start of the loaded move). Secondly, the network in question (where the scheduled services are and if the truck availability is the bottleneck), and thirdly, the specifications of the transport demand.

In conclusion, the impact of combining the routes of containers and trucks can be a decrease of costs and emissions. However, it depends on the location of the demand, the network, the availability of trucks and the costs of all parameters. If there are limited trucks available with limited time, the possible benefits increase.

Contents

1
Introduction

In this chapter, the scope of the research is introduced. First, the background information is provided on global transport (Section 1.1) and the role of synchromodal transport (Section 1.2). Section 1.3 summarizes the relevant previous studies in this field. Section 1.4 identifies the research gap in the literature of transport routing models and reflects on the drawbacks of missing this information. In Section 1.5 the added value by closing the research gap is motivated. In Section 1.6 the research gap is translated to a research question with sub questions. The structure of the report is given in Section 1.7.

1.1. Background

Global transport of containers has increased significantly in the last decades. A lot of the global transport of goods is transported by containers, which results in an increase in container throughput at container terminals [36]. To handle larger volumes of containers, terminals increase their expenses on improving the container throughput in the terminal, for instance in Rotterdam [39]. According to Langen and Pallis [25] the hinterland accessibility is as important as the container throughput of the terminal and has obtained an increasing importance in the seaports competitiveness. In Europe there are several seaports competing which have invested in the transport networks around the ports, for instance the ports in the region of Le-Havre-Hamburg [24]. Without investing in efficient and well-functioning hinterland transport chains a seaport can lose attractiveness to shippers and carriers. More efficient hinterland container transport helps to release containers faster and reduce the congestion in and around seaports [7].

To transport containers inland, there are several transport options, truck, by ship, or by train. In 2018, road transport was the leading mode of freight transport in the European Union (52.4%) followed by maritime transport (30.0%) and rail transport (13.0%) [14]. Unimodal road transport is even more dominant in other countries. Road transport has several advantages such as flexibility and speed for hinterland transport, but is undesirable when considering the social and environmental impacts [42]. An important issue in the regions around the main seaports is traffic congestion. The reason for this is that the roads around the terminals are not constructed for the growth in container throughput in combination with commuters [30]. The increased amount of container travels by road can cause a negative environmental impact. It is estimated that for an import or export container the amount of emission CO_2 per kilometer if carried by a small (inland) container ship is 5.6 CO_2/tonne-km and 155 CO_2/tonne-km for trucks [27].

Increasing the efficiency of transport can increase the throughput of containers and decrease the costs and emissions of CO_2 per container. To decrease the cost and the emissions of trucks and containers, the ideal transport routes have to be determined for all modes of transport considering the routes and options. Determining the ideal routes in real-time can be seen as the final goal for the future.

1.2. Synchromodal transport

Improving the efficiency of freight transport can be done by integrating the freight transport chain. In the time span of over 35 years, five different concepts relating to freight transport have been introduced [41]. The concepts are: Multimodal Transport, Intermodal Transport, Combined Transport, Co-modal Transport, and Synchromodal Transport.

Multimodal Transport is the carriage of goods by two or more modes of transport [47]. Intermodal Transport considers the integration of the transport modes into one system from start to end. This includes active coordination. The aim of Intermodal Transport is to improve the overall efficiency of the transport system. Combined Transport can be seen as Intermodal Transport with the added dimension of sustainability. Comodal Transport can be seen as Intermodal Transport with a focus on efficiency.

Synchromodal Transport is the most recent concept. A definition for synchromodality is: "Mode choice is made along with the production of the transport service, based on real-time information on the current conditions of the transport system"[41]. When considering the hinterland network, it results in making the mode choice for a container between truck, train, and ship. And integrating the modes and containers based on real-time information on the routes. Within a synchromodal system delays, congestion, reliability, pricing, availability transit times, etc. can be improved. By including these factors in the routing decision, it can result in increased reliability and efficiency in the network.

1.3. Related work

In literature on freight routing, there are three different decision groups: strategic planning, which determines the long-term planning (such as the location of hubs), tactical planning which determine the medium-term decisions (such as the location of roads) and the operational planning, which determines for instance how a truck travels through the network. Several studies have been addressing the strategic and tactical planning, but only a few have been focusing on the operational level [17]. Synchromodal Transport is focused on the operational level of transport, but even in this field there is limited research available. There are still large gaps in the literature regarding models for integrated network planning, methods for real-time decision making, and methods for creating flexibility in the transport planning problem [48].

Recent models such as the model of Behdani et al. (2016) [7] integrate the routing of container transport with ship and trains. The routing of the trucks is not included in the model, and the trucks are assumed as always available. It is furthermore often assumed that trucks are always available for the transport of containers. This assumption is analysed by [26] which includes the kilometers of a truck when it is not transporting containers. This is the first study to the authors knowledge which considers empty kilometers of the trucks in the synchromodal transport network. The trucks and containers are routed as flows within the network using model predictive control. The result of the research was that the assumption that trucks are always instantly available at a location significantly changes the optimal route. However, a model that can individually route both trucks and containers is not yet available.

1.4. Problem context

Current synchromodal container transport models consider that trucks are available at all locations and do not include the entire routing of the truck and the availability of the truck. Not including the entire route of the truck and the availability of the truck is an assumption that could have significant influences on the result. Because of this assumption, the optimal route for the container is determined without considering the optimal route of the truck. Truck transport is often the least environmentally friendly and is the most cost expensive [26], it is thus important that container routes do not enforce bad truck routes.

If the entire routes of trucks are not considered, the travel distances of the truck when it is not transporting a container are not included in the entire routing decision. For instance, the trip to the pickup and delivery point is missing and the empty trip between nodes. The empty kilometers of a truck is not considered. When the truck is loaded, the truck is earning money, and when the truck is traveling empty the truck is costing money. When optimizing the route of the truck, the truck should decrease the amount of empty travel distance. The empty distances are in the first ride, and the last ride (from and to the depot), and between the different transport jobs. For instance, considering the routing between location A, B, and C, in combination with different jobs; traveling from location A to location B and thereafter from location B to location C is more efficient than when the truck travels from location A to location B followed by traveling from location C to location B, see Figure 1.1.

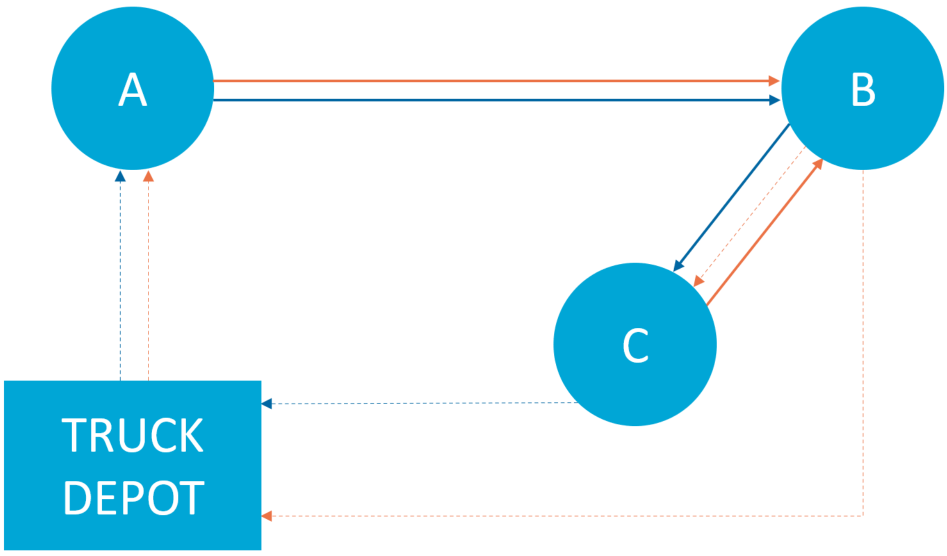

Figure 1.1: Truck routing problem, where the lines are loaded trucks and the stripes are the empty trips of trucks

When the trucks are assumed always and infinitely available, the total truck capacity is not included. A container terminal can be located close to a container terminal and can have a lot of trucks, but this does not result in infinitely available trucks at any time. Next to the limitation of the total truck capacity, the road routes a truck is using has also limitations. Traffic jams often occur around deep-sea terminals and should be considered in the loaded and empty trips. The traffic situation on the road (such as traffic jams) and the dynamic environment at terminals are a problem in container and truck transport. According to Crainic and Kim (2007) [11], truckload carriers operate in a highly dynamic environment. There is little known with certainty regarding the waiting delays at customer locations, precise locations of loaded and empty containers at later moments in time, future demands, and so on. If the entire route of the truck is analysed there can be more understanding in the road sections where the truck could be delayed. Research is necessary to improve the vehicle utilization of container trucks in freight transport model in such a way that costs, quality, and emissions are improved. This could lead to improved understanding of the dynamic environment for containers and trucks in future research.

1.5. Relevance of research

Synchromodal transport is a relatively new field of research with a limited number of existing models. Existing models route the containers through the synchromodal network. A clear gap in the literature is the individual routing of both the trucks and containers within a synchromodal network. This research finds out what consequences it has to leave out the routing of the individual truck. By routing individual routes of the trucks and containers, this research includes empty trips and the capacity of trucks. This can result in different optimal routes for containers through a synchromodal network, which has an impact on the costs, CO_2 emissions and the quality of service.

Costs of the trucks during transport are based on the distance and the time spend. When considering the integration of the trucks and containers, the trucks can work together to transport. This way the costs of the total network can be decreased. Trucks emit CO_2 which has obtained increased focus last years. Compared to other modes, the truck emits per container more CO_2, so decreasing the empty kilometers results in significant emission reduction. When achieving an increased understanding of the network capacity limitations in truck transport, the quality of the service can increase. With the quality of service the reliability of arriving before the due date for containers and trucks is meant. This research can be a step towards a fully synchromodal hinterland transport network, by improving the integration of truck routes in the synchromodal container network.

1.6. Research questions

The aim of this research is to study the impact of integrated planning by developing a method that is capable of routing individual containers and trucks through a synchromodal network in an optimal way, considering costs, distance and emissions. The model decides how the containers travel (by truck, or by a combination with ship and/or train) and the route of the trucks (when the trucks are full and when the trucks are empty). This model should be able to decrease the synchromodal transport costs and CO_2 emission and increase the quality of the transport. The following is the main research question:

"What is the impact of combined truck and container routing through a synchromodal transportation network?"

To investigate the impact of combined truck and container routing, we developed a model considering a Synchromodal Transport system. The model considers a static, deterministic, multi commodity problem with scheduled services (ship and train) and individual routing of containers and trucks. The ICTR model, which integrates the route of the container and the trucks is compared with the benchmark model, which first determines the route for the containers followed by determining the route of the truck. The results will show what the impact is of the assumption of the current container routing models that trucks are always available compared to the situation that individual trucks route through the network.

The research question is broken down into several sub questions. The first sub question explores the current transport models available and what can be learned from those models. The second question sets the direction of the research, with the Key Performance Indicators (KPI) the objective function(s) can be determined. The third sub question explains the used method to build the joint optimization models. The fourth sub question is considering which scenarios to use in the experiments to find out what impact the integrated routing of containers and trucks can have. The next sub question discusses the results of the scenarios and can answer the research question. The question evaluates the possible contribution of this research towards decreasing the transport costs and the CO_2 emissions. The final question evaluates the impact of the individual routing of containers and trucks on the modal split and the number of empty kilometers of the truck.

1. What current routing models are available in synchromodal transport systems?
2. What are the KPIs in synchromodal transportation?
3. How can a joint optimization model for container and truck routing be developed?
4. What are relevant scenarios for the experiments to evaluate the performance of the proposed joint optimization model?
5. What is the impact of the individual routing of container and truck on the cost and the amount of CO_2 emission?
6. What is the impact of the individual routing of container and truck on the modal split and the amount of kilometers trucks drive empty?

1.7. Outline

Firstly, in Chapter 2 the literature is introduced where the existing routing models and the KPIs in synchromodal transport are explained. Secondly, in Chapter 3, the method is given to develop the joint optimization model. Chapter 4 explains the performed experiments and shows the impact of the model on the KPIs. Finally, in Chapter 5 the research question is answered and possibilities for future research are given.

2
Literature Review

In this chapter, the literature background is introduced, in such a way that after this chapter synchromodal transport is explained, existing models are introduced and the KPIs are described. The differences within the synchromodal transport definition, the modes involved, the potential, and the challenges are presented in Section 2.1. Followed by analysing in Section 2.2 what models are available within the intermodal and synchromodal transport spectrum and determine which could be used for this research. Section 2.3 sums up the key performance indicators in synchromodal transport. Finally, in Section 2.4 a literature summary is given.

2.1. Synchromodality

Synchromodal Transport is a recently introduced term based on several already existing terms. This section introduces and defines the term of Synchromodal Transport and the already existing terms in section 2.1.1. Introduces the transport modes used in hinterland transport, its advantages and disadvantages in section 2.1.2. And finally, explains what the purported benefits and challenges are of Synchromodal Transport in section 2.1.3.

2.1.1. Definition

This section gives more insight into the definition of synchromodality and what it is based on, by first introducing the definition of using a single mode followed by the definition of using multiple modes and the differences in these definitions.

When a container is picked up and delivered using a single mode of transport, the concept of transport is called uni-modal transport. Despite the fact that linking the transport chain by different modes of transport is discussed for years, unimodal road transport is still the most preferred hinterland transport [46]. According to Reis (2015)[41] there are several different concepts to integrate the transport chain. The following concepts will be discussed in this section: Multimodal Transport, Intermodal Transport, Combined Transport, Co-modal Transport and Synchromodal Transport.

Multimodal transport is transport of a container using multiple modes. Intermodal transport uses multiple modes and integrates for a unit load the door-to-door transport. Combined transport introduces within the intermodal transport the component of sustainability. Co-modal transport introduces within the intermodal transport the component of efficiency.

Synchromodal transport is in addition to these other definitions, adding the concept of adaptive mode choice. According to Tavasszy et al. (2015) [46] "Synchromodality, or synchronized intermodality, can be briefly summarized as the vision of a network of well-synchronized and interconnected transport modes, which together cater for the aggregate transport demand and can dynamically adapt to the individual and instantaneous needs of network users." This means that the mode choice is made along with the production of the transport service. The difference compared to the other transport concepts is that the choice is made in real-time during transport. Figure 2.1 shows the differences between the transport concepts.

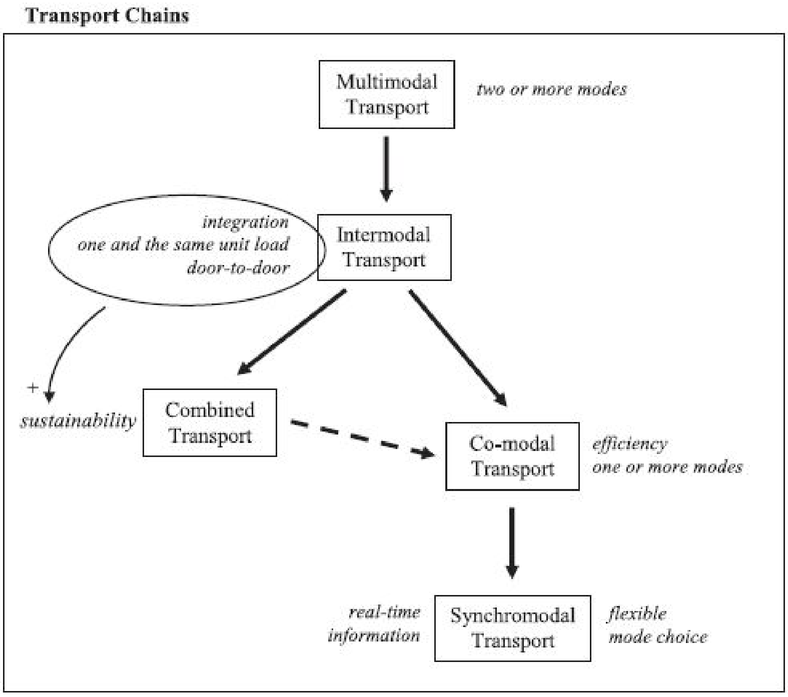

Figure 2.1: Sequential relations between transport concepts [41]

2.1.2. Modes of the synchromodal transport chain

In this section, the modes involved in hinterland container transport around the port of Rotterdam are introduced. The seaport container terminals of Rotterdam can have, contact to sea, inland waterway, rail, and road [39][19]. Terminals in the hinterland can have contact to the inland waterway, rail, and road. In hinterland transport the sea-transport is an input.

The transport chain is partitioned into three segments: the pre-haul (which is the first mile for the pickup process), the long-haul (which is the hub-to-hub transit of containers), and the end-haul (which is the last mile of the delivery process). The pre-haul and the end haul are in most cases carried out via road transport. The long haul considers next to road transport also transport via rail and water modes. The long haul transport usually considers the involvement of multiple transport modes [45][46]. The transportation between terminals can be dependent on the accessibility of the terminal by all hinterland modes [46]. The pre-haul is the part of the trip where it is transported from a customer towards a container terminal/hub, and the end-haul is the part of the transport of a container where it is travelling from the container terminal/hub towards the location of the customer.

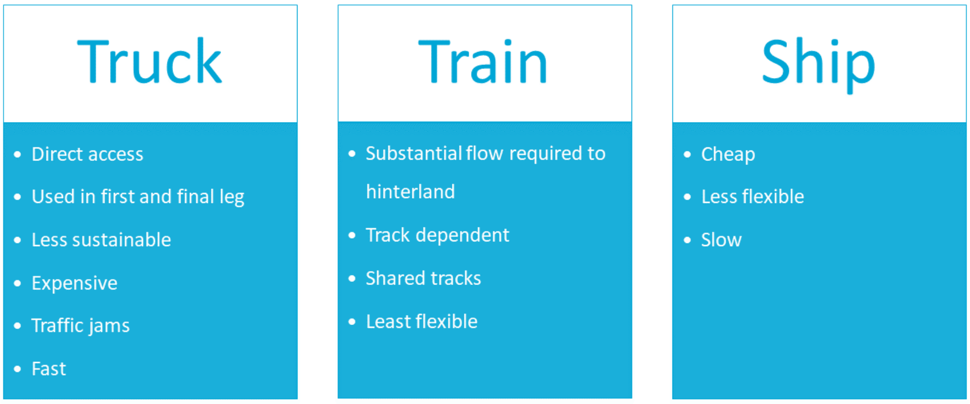

Figure 2.2: Different modes and characteristics

When considering the modes (trucks, trains, and ships) they have differences in costs, environmental impact and flexibility. The differences can be seen in Figure 2.2 based on [46]. Trucks are the most frequent used travel mode, and travel by road is available to all terminals/hubs and transport 1 to 2 containers. So, the trucks have the advantage of being flexible and fast. Because of the direct access of the road to all terminals and customers, the container is transported by truck mostly in the first and final leg of the journey.

Because a truck has limited space for containers, there are a lot of trucks required to transport a lot of containers. This causes truck container transport to be relatively less sustainable compared to the other modes. Also, a truck requires a driver, which compared to other transport modes results in higher personnel costs.

Trains have the advantage of using electricity and being quick. Which results in the most sustainable container transport option. The downside of trains is that trains are track dependent and that the tracks can be busy. Due to the busy tracks, the train is the least flexible option. To make train transport profitable, the train requires a substantial flow to the hinterland.

Ships have the advantage of being the cheapest compared to the other container transport modes. There are different uncertainties for ships such as busy locks and changing water levels. Compared to truck transport, ship transport is more sustainable due to the number of containers transported. The disadvantage of ships is that the travel-velocity of ships is low compared to other modes. Furthermore, to use ships, water access is required for a terminal. This results in less flexibility in transport compared to trucks, but more flexibility compared to trains.

All the transport modes have their advantages and disadvantages, combining the advantages of each will result in the optimal use of the network.

2.1.3. Potential and challenges of the synchromodal transport routing

Currently, uni-modal road transport is the most frequently used mode of transport for containers [14]. This has the advantage that the transportation in such a system is highly flexible, but the disadvantage of being costly, being part of traffic jams and it is less sustainable. Optimizing uni-modal transport is considered as vertical integration. Vertical integration has the aim to optimize the operation of moving resources and stationery resources. Horizontal transport considers the integration of multiple modalities as a single transport service [7]. For Synchromodal Transport, vertical and horizontal is required, which can be seen in Figure [2.3]. A network that is horizontally and vertically integrated could result in better overall network performance. Synchronization of ship, train, containers, and trucks could lead to seamless operations, with reduced waiting time, storage, and total transportation costs. Furthermore, due to the synchronisation there can be positive effects on the joint optimized services. Because of the effects on the responsiveness of the vehicles and the increased possibility to customize the route during the transport.

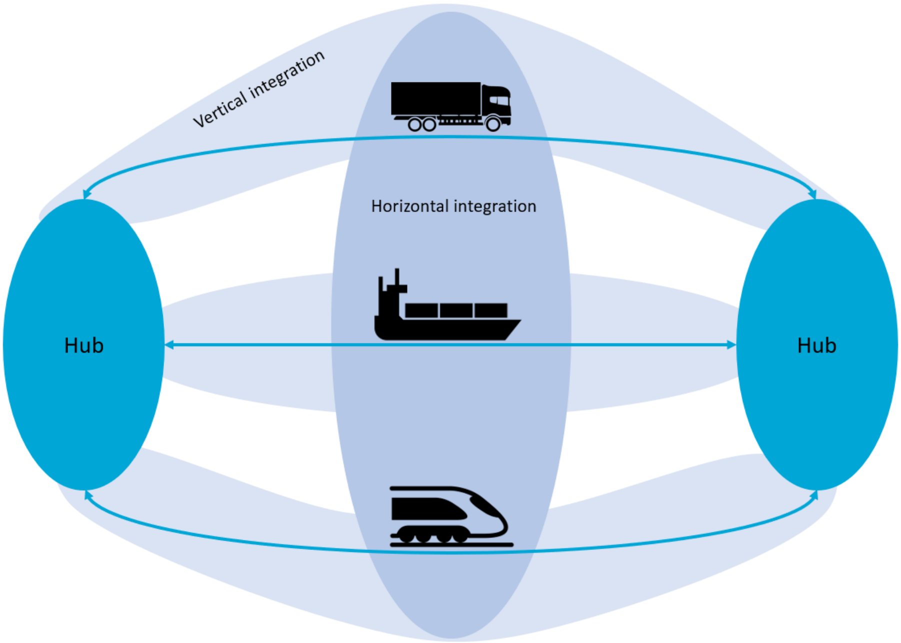

Figure 2.3: Modes and integration in synchromodal transport

According to literature [48], the challenges in implementing Synchromodal Transport are threefold. Firstly, there are currently no suitable methods for creating an integrated network plan. Secondly, adapting that plan into real-time decision making to react to delays and other spontaneous changes. And thirdly, because of the customer restrictions with its transportation orders, the network misses the flexibility to switch between modes and routes and cannot achieve the benefits of synchromodal planning. This research focuses on a method for creating an integrated network plan by including the routes of the trucks. Future research will be required for the other gaps in the topic of Synchromodal Transport.

2.2. Models available

When considering transport models there is a wide variety of models available. This section first analyses the available transport models, when considering the modal choice and the individual route of a vehicle. Followed by selecting the most relevant models. Finally, the relevant models are compared to the Integrated Container and Truck Routing (ICTR) model of this thesis.

2.2.1. Transportation models considering multiple modes

This section firstly shows the different types of transport models which consider multiple modes, followed by analysing which model types are relevant to the research, and finally evaluates the most relevant models. When considering container transport models, three different planning horizons can be defined. The decision horizon levels are: strategic, tactical, and operational [45].

Strategic planning

The strategic planning problems considered in multimodal freight transport relates to the investment decisions on the present infrastructures. An example is the model of Meng[32], which determines the intermodal hub-and-spoke network based on investment budget limits and different stakeholders. The goal of the model is to decrease the total transport costs by locating the hub on the optimal location. Other strategic models also include the capacity of the arcs, for instance due to congestion [21].

Strategic considerations are required when optimizing the infrastructure or choosing the locations of the hubs. For this research it is out-of-scope since it focuses on optimally using a given network, so the strategic planning models are not further analysed.

Tactical planning

Tactical planning problems deal with optimally utilizing the given infrastructure, by choosing the services and transportation modes. For a container the decision is made on which terminals to use and what service to consider, without deciding the specific route. A service (ship and train) has an origin, destination, and intermediate terminals, its transportation mode, route, and its service capacity. A Mode has a Loading capacity, speed, and price. There can be two categories defined in Tactical planning models, the flow planning models and secondly the Service network design models [45].

Table 2.1 presents the analysed tactical models. The models are divided into the modes which are scheduled and the types of the model: flow, static, and dynamic.

The flow planning models lead to decisions on the movement of commodities through the network. The category of flow models considers the input of commodities as "flow" instead of as individual commodities.

One example is the research of Meng [33] which proposes a liner ship fleet planning problem that takes the containers into account. The containers are introduced as an average approximation. Another flow planning example is train scheduling, where Verma [50] considers flow variables for the container input and optimizes the schedule for the trains while considering the total costs and the risks during transport.

Both service network design models plan the service schedules including the transportation services and modes for the commodities. The service network design models can be divided into static and dynamic problems. The static problems determine the equipment planning, the routing, the flow of commodities, and the capacity allocation. For dynamic problems at least one feature varies over time.

This research routes the containers/commodities and trucks individually through the network, where the trains and ships are assumed as scheduled. From the tactical problems the mode choice of the container is interesting. Because this thesis model does choose the mode of transport implicitly. When applying the criteria of using a static model and that multiple modes are used, the model of Ayar and Yaman (2012) [5] and the model of Pazour et al. (2010) [37] could provide an insight into the part of the mode choice for in the model.

The paper of Pazour [37] considers person transport on high-speed rail network and has the aim to reduce traffic jams in the United States of America, by using an uncapacitated network design model. However, in this model it is not possible to follow individual commodities/persons. The paper of Ayar and Yaman (2012) [5], gives a multi-commodity routing problem with scheduled services. This paper is relevant for the research and further analysed in Section 2.2.3.

Table 2.1: Tactical models

	Flow	Static	Dynamic
Ship	Meng et al. (2011b) [31] Meng et al. (2012) [33]	Gelareh et al. (2011) [15] Hsu et al. (2007) [20] Shintani et al. (2007) [43] Caris et al. (2012) [10]	Agarwal et al. (2008) [1]
Train	Verma et al. (2010) [49] Verma et al. (2012) [50]	Anghinolfi et al. (2011) [4]	Andersen (2009) [2] Andersen et al. (2009) [3] Pedersen et al. (2009) [38] Zhu et al. (2014) [52]
Truck			Hoff et al. (2010) [18] Lium et al. (2009) [28]
Ship & Truck		Ayar et al. (2012) [5]	
Truck & Train		Pazour et al. (2010) [37]	Moccia et al. (2011) [35]

Operational planning

"On operational planning level, we still look for the best choice of services and associated transportation modes, best itineraries and allocation of resources to the demand. However, we need to answer the real-time requirements of all multimodal operators, carriers and shippers." is stated in Steadieseifi[45], this means that in contrast to the tactical level of planning, the individual routing of containers is analysed but not all operational models are real-time. This results in more calculation intensive models, which are often solved by approximation.

In Table 2.2, the literature of of Steadieseifi et al. (2014) [45] is extended with recent literature and analysed based on the mode(s) used. The available operational planning models be divided into fleet management and resource allocation models, and itinerary re-planning models.

The fleet management and resource allocation problems focus on decisions such as: (re)positioning and storing. For instance, in the paper of Lam (2007) [23] uses an approximate dynamic programming approach for the allocation of empty containers. Or for example, the paper of Erara (2005) [13] focuses on asset management problems faced by container operators. The problem is formulated as an operational container management problem as a large-scale multi-commodity flow problem on a time-discretised network.

The itinerary re-planning problems focus on the real-time optimization of routes, which can consider operational disturbances and multi-modal routes, for instance, Bock (2010) [9], introduces a real-time control approach for transshipment and dynamic handling of disturbances and accidents. The research of Goel (2010) [16] combines the shipment and route choice for assets moving through a multi-modal network, where the trucks are assumed always unlimited available. More up to date itinerary re-planning models are the papers of Guo et al. (2020) [17], Larsen et al. (2019) [26], Qu et al. (2019) [40], Mes and Iacob (2016) [34] and Behdani et al. (2016) [7].

This research is an operational model for itinerary planning because of the individual routing of containers and trucks. The most up to date models with those specifications can be seen in 2.2. These models are relevant for this research and further analysed in Section 2.2.3.

Table 2.2: Operational models

	Fleet management and resource allocation	**Itinerary Re-planning**
Ship	Di Francesco et al. (2013) [12] Lam et al. (2007) [23] Song and Dong (2012) [44]	
Train		
Truck		
Ship and Truck		Bock (2010) [9] Goel (2010) [16]
Truck and Train	Bandeira et al. (2009) [6]	
Ship and Train		
Truck, Train and Ship	Erera et al. (2005) [13]	Guo et al. (2020) [17] Larsen et al. (2019) [26] Qu et al. (2019) [40] Behdani et al. (2016) [7] Mes and Iacob (2016) [34]

2.2.2. Truck routing models

When considering the individual route of trucks that are transporting containers there are several steps during a trip. The trucks start at a depot, pick up a container, deliver a container, and then decide if there is another container to pick up and deliver or to go to the same or another depot. A truck must be able to drive over an arc multiple times, because it must be able to transport different containers over the same road. It should also be possible to follow each move of a truck and determine if the capacity of the truck is used and which specific container it is transporting. Most important of all this is to do it in an optimal way. Zhen (2020) [51] evaluates the literature of the Vehicle Routing Problems (VRP) and proposes an interesting model which is able to pick up and deliver goods and individually route trucks to do so.

There are several different vehicle routing problems available, an overview is given in Table 2.3. In this table the options of a VRP are shown. The first vehicle routing problem (VRP), which selected the optimal route for a vehicle to a set of customers. The VRP had the following assumptions: each vehicle must depart and return to the same depot; each customer must be served exactly once and there is a single depot. Over the years the vehicle routing problem has advanced to consider time windows for the transported goods (VRPTW).

A multi-depot VRPTW (Multi-D VRPTW) is the next step. This variant serves customers based on multiple depots and the start location and final location must be for each truck at the same depot. A multi-trip VRPTW (Multi-T VRPTW) has the option for trucks to do multiple trips (visits to the depot). A multi-trip and multi-terminal problem with VRPTW and release dates (Multi-D&T VRPTW-R) is presented in [51]. The truck routing of the IRCT model proposed in this research is based on the model of [51] which routes vehicles but does not consider the intermodal network. This way it is possible for trucks to visit nodes and arcs multiple times and still be able to know the exact time that truck at a specific location. In Table 2.3 methods for vehicle routing problems and the IRCT model are compared.

Table 2.3: Different VRP problems

	Depot	**O & D**	**Serving customer**	**Time windows**	**Multiple trips**	**Release date (associated with customers)**
VRP	Single	Same	Once	N	N	N
VRPTW	Single	Same	Once	Y	N	N
Multi-D VRP	Multiple	Same	Once	N	N	N
Multi-D VRPTW	Multiple	Same	Once	Y	N	N
Multi-T VRPTW	Single	Same	Once	Y	Y	N
Multi-T VRPTW-R	Single	Same	Once	Y	Y	Y
Multi-D&T VRPTW-R	Multiple		Once	Y	Y	Y
This thesis	Multiple		Multiple	Y	Y	Y

2.2.3. Most relevant studies

The most relevant models for this research are determined in Section 2.2 and summarized in Table 2.2. In this section, we give a detailed overview of these models followed by a thorough introduction of each. Table 2.4 gives an overview of the model specification and how this thesis relates to those models. The table shows if the model is Tactical or Operational (T/O). What modes are used in the model, Truck (Tr) and Ship (Sh) or truck, ship, and train (All). If empty truck trips (ETT) are considered to some extend. If the trucks are routed individually (Individual Routing of Trucks (IRT)) and if the containers are routed individually (Individual Routing of Containers (IRC)). If the model inputs do not vary over time which is indicated as Static(S) or vary over time which is indicated as Dynamic (D). If the solution is Approximated (app) or Optimal (Opt). Finally, what kind of network is used, a network with two nodes with one single origin and destination (single OD) or using multiple nodes (multi).

	T/O	Modes	ETT	IRT	ICR	S/D	App/Opt	Network
Guo (2020)	O	All	No	No	No	D	App	multi
Zhen (2020)	O	Truck	Yes	Yes	No	S	Opt	multi
Larsen (2019)	O	All	Yes	No	No	D	App	multi
Qu (2019)	O	All	No	No	No	D	App	multi
Behdani (2016)	O	All	No	No	No	S	Opt	single OD
Mes (2016)	O	All	No	No	No	D	App	multi
Ayar (2012)	T	Tr&Ba	No	No	Yes	S	Opt	multi
This thesis	O	All	Yes	Yes	Yes	S	Opt	multi

Table 2.4: Overview of models

Guo (2020)

Guo (2020) [17] introduces an online synchromodal matching problem to match transport services and shipment requests. The objective is to minimize the total costs of the problem over a given planning horizon. She designs a heuristic algorithm that solves the dynamic planning problem in an efficient way. The model is a dynamic and stochastic shipment routing model, which involves all modes of transport. The trucks are routed as capacitated vehicles with fixed routes and flexible departure times. Compared to this thesis model, the model of Guo does not consider a deterministic result, individual routes of containers and trucks and empty truck kilometers. The trucks in the model are assumed always and unlimited available.

Zhen (2020)

The model of Zhen (2020) [51] is a uni-modal model, considering only road transport. The problem is a multi-trip multi-depot vehicle routing problem with time windows and release dates. The goal of this research is to minimize the travel time as a mixed-integer programming model. The experiments with this model show that with certain algorithms a near-optimal solution can be found for problems up to 200 demand, 20 depots, and 40 vehicles. To solve problems with increased numbers of demand, depots, and vehicles there are two algorithms developed: the hybrid particle swarm optimization algorithm and a hybrid genetic algorithm. Compared to this thesis model, the model of Zhen does not consider the individual route of containers and other modes of transport than trucks. This means that the model of Zhen does not route individual containers through a network.

Larsen (2019)

The model of Larsen (2019) [26] focuses on the optimal use of ship, rail, and truck transport. With the aim to find an overall efficient solution, taking future actions into account. Larsen focuses on the challenge to integrate container and truck planning in a synchromodal network, using model predictive control (MPC). Compared to the other models, the model considers empty truck travels. The model, however, considers trucks and containers as flows and can thus not guarantee time-constraints for individual trucks and containers. This results in that there is no individual routing of trucks and containers, so it has not an optimal solution but it approximates the solution.

Qu (2019)

The model of Qu (2019) [40] focuses on the unexpected uncertainties which could cause deviation from the original plan. This mixed-integer programming model is able to re-plan the freight transport in the hinterland. It uses flow routing for containers. Compared to this thesis model the model of Qu firstly, does not route the container and the truck individually secondly, assumes trucks as always available thirdly, assumes different inputs over time, and is dynamic and finally approximates the solution.

Mes (2016)

Mes (2016) [34] is a model which is solving the problem known as the multi-objective k-shortest path problem, where the shortest path for the container through the network is found, taking into account schedules of trains and ships, closing times of hubs and time-windows of orders. The main goal of the model is to decrease CO_2 emissions. Compared to this thesis model the model of Mes firstly, does not route the container and the truck individually secondly, assumes trucks as always available thirdly, assumes different inputs over time and is dynamic, and finally approximates the solution.

Behdani (2016)

Behdani (2016) [7] optimizes the schedule of the trains and ships, assuming that all trucks are always available in unlimited numbers. The model considers a single origin-destination path, with a static demand. Compared to this thesis the model of Behdani does not consider a network with multiple nodes, and it does not consider the individual routing of containers and trucks.

Ayar (2012)

The research considers a routing problem for multiple commodities through an intermodal network that includes trucks and ship transportation. "Given a planning horizon, a set of commodities to be picked up at their pickup times and to be delivered not later than their due dates, the problem is to decide on routes for these commodities using trucks and scheduled and capacitated maritime services at minimum cost of transportation and stocking at the seaports" [5]. Compared to this thesis model the model of Ayar does not consider firstly, all modes of transport. The train is not included in the network and model of Ayar. Secondly, the route of an individual truck is not included, the model assumes that trucks are always and unlimited available.

This thesis

The model presented in this research is a multi-mode, operational, static, and deterministic model that considers all modes of transport. The ships and trains are modeled as scheduled services, and the trucks and containers are routed individually through the network. The basis of this model is the mode choice procedure of Ayar (2012)[5] and the detailed individual routing of the trucks by Zhen(2020)[51]. This thesis combines those two models and furthermore considers the constraints to determine which container is transported with which truck, constraints for specific time windows for containers and trucks, and constraints to include trains in the network. For each container in this thesis, it is clear how it routes through the network and on which moves it uses a specific truck, so empty truck moves can be included. This model is the first model that integrates the individual truck and the container route through the synchromodal network.

2.3. Key performance indicators in intermodal transport

Synchromodal transport is possible when multiple transport chains are integrated. Each transport chain has many companies involved, such as terminal operators, transport operators and etc., who all have the primary objective to optimize the goals of their own company [19]. For instance, a truck company has the goal to reduce costs and increase profits by having more trips that are optimally connected to each other, but it has to compete with other truck companies. To achieve the projected benefits from synchromodal transport, an integrated network and cooperating companies are required. Else, due to the self-serving behaviour there could be poor performance in the network due to inefficient routing and waiting times.

In commodity transport problems, to decrease the complexity, the role of all the individual stakeholders is ignored, and the whole system is managed by one single central party [45]. In reality, companies are competing with each other in a dynamic market. On the one side, there are the customers who demand the cheapest service with the highest quality and on the other side, there are the companies, of the shippers, trucks, railway personnel and the terminal operators. What all the stakeholders have in common that the companies want to optimize their own goals, which are in most of the times the costs of the transport and being, as a network, competitive to other networks.

To determine how a transport network is performing Key Performance Indicators where the different decision models can be compared to, have to be determined. Based on the stakeholders the main goal is to decrease the total network costs. The KPIs in the most relevant studies and this thesis model can be seen in Table 2.5. All the models consider the total costs of the network as the objective to minimize. In the table can the difference be seen between the models on what is included and excluded in the total cost. There can also be seen that some research has KPIs which are not in the objective function.

The modal split is determined by the travel distance of a container using a certain mode divided by the total transport distance of that container. The modal choice of the model can be indicated by this KPI. Based on this result the preferred mode of transport can be seen, this shows if the model chooses to use less unimodal transport. The waiting time of containers at nodes is included in most of the relevant research, with an amount of cost per time. Storing a container at a certain location costs money. The waiting time also indicates how long a container has been standing still in the network. This is included in the objective to motivate the model to decrease the total transport time and to create a more realistic model. In recent years there is an increased interest in decreasing CO_2 emissions. In some research, it is an objective and implemented in the cost function by a tax per CO_2 emissions tonne per kilometer usage of a certain mode [17][34]. In other papers, the amount of CO_2 is a KPI, but not the objective. In the case of this thesis which has the aim of integrating trucks and containers, the amount of emission is a KPI and not the primary goal of this research, because stakeholders make decisions primarily based on costs.

Empty truck kilometers cost money, but are not considered in most papers not considered in the objective function, except for the model of Larsen (2019)[26] and this thesis. This thesis is the only research available to the authors knowledge that is considering the entire route of the truck and is able to determine what the effective kilometers are. The trucks effective kilometers, which is the number of loaded kilometers of a truck divided by the total distance of the truck, indicates if the truck is used optimal or not.

In the case of this research, the situation where the route of the container is determined with the consideration of truck capacity is compared to when the container route is determined when trucks are always available. This thesis Model has the objective to decrease the costs of the total network. Which considers the entire trip of the truck, from leaving the depot to returning at the depot and the entire trip of the container, including all modes used by the container. The key performance indicators of this thesis model are the modal the total costs, per mode, the modal split, the waiting time, the CO_2 emitted, and the truck efficiency.

	Modes	**Total costs**	**Modal split**	**Waiting time**	**CO_2**	**Empty truck**	**Truck efficiency**
Guo (2020)	All	Obj		Obj	Obj		
Zhen (2020)	Truck	Obj					
Larsen (2019)	All	Obj		Obj	KPI	Obj	
Qu (2019)	All	Obj		Obj			
Behdani (2016)	All	Obj	KPI	Obj			
Mes (2016)	All	Obj			Obj		
Ayar (2012)	Tr & Ba	Obj		Obj			
this thesis	All	Obj	KPI	Obj	KPI	Obj	KPI

Table 2.5: Overview of models

2.4. Summary

This chapter answers the first two sub questions by analysing the existing routing models available in synchromodal transport and indicating the frequently used KPIs in state-of-the-art synchromodal transport models. This research focuses on the operational problem of routing containers and trucks. There are numerous models available that consider operational transport optimization, but there is no model available which is able to solve the routing of individual trucks and containers through a synchromodal network.

The key performance indicators in synchromodal transport are costs, CO_2, time costs, and waiting time costs. This research can in contrast to other models, focus on the effective kilometers of the truck as a KPI because it can track the empty kilometers as well and indicate how effective a truck is used in the network. With the information gathered in this literature chapter, the next Chapter 3 formulates the model mathematically.

3

Methodology

To analyse what the advantage could be to integrate the truck route and the container route in a synchromodal network, the Integrated Container and Truck Routing (ICTR) model and the benchmark model are created. Both are new models that are routing the trucks and the containers.

The ICTR model determines the optimal route for the containers, considering the entire trip of the trucks. The benchmark model considers, first that trucks are always available, when determining the route of the container, followed by finding the optimal route with the available trucks.

This chapter explains how the joint optimization model for containers and trucks through a synchromodal network can be developed based on the literature review of Chapter 1.3. In Section 3.1 it is first described how the modeling approach was selected. Hereafter, the conceptual model is introduced in Section 3.2. Finally, the mathematical models of the ICTR model and the benchmark model are presented. The section concludes with a summary of this chapter.

3.1. Selection of the modeling approach

This thesis has the aim to find out what the impact is of combined truck and container routing through a synchromodal transportation network. Therefore, two different new models are created, first the integrated container and truck routing model (ICTR), and secondly the benchmark model which represents the assumption of existing models. Both models should be able to route trucks and containers individually through the network to find out what route decisions are different when combining the truck and container routes.

The ICTR model integrates the individual routes of trucks and containers to find the optimal solution. There is no existing model where the results of the ICTR model can be compared to. Therefore, the benchmark model is created. The benchmark model first routes the containers based on the assumption of existing models, that assume that trucks are always and unlimited available, followed by finding the optimal route for the available trucks based on their capacity. The output of the benchmark is the optimal route for trucks when the route of the containers is already determined. By comparing the ICTR model and the benchmark model, the added value by the integration of the route of containers and trucks is analysed. Both models are new models that can route the trucks.

3.2. Conceptual model

The proposed benchmark and the ICTR model are static and deterministic. The models know upfront what the demand is for the time span of the model. Both individually route the containers and trucks through the system. Figure 3.1 shows an overview of the inputs and the outputs of both models.

3.2.1. Inputs of the model

The inputs of the model consist of parameters of the network, containers, trucks, trains, and ships. In the following subsections, the different inputs and their underlying assumptions are described.

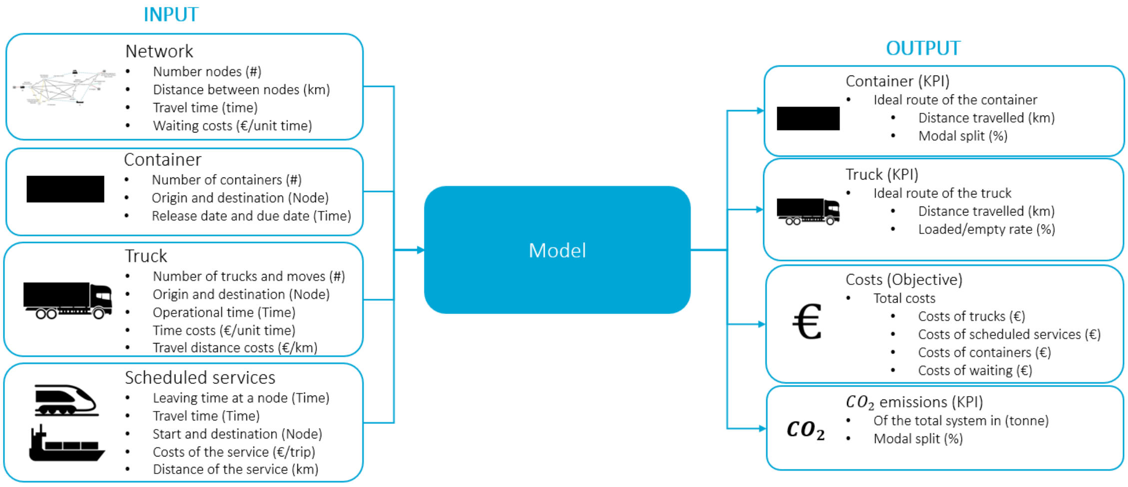

Figure 3.1: Model overview

Network

The network in the model is composed of arcs and nodes. The nodes are the hubs, at the hubs the containers can switch mode and can travel over the arcs by transport modes. There are two different transport networks used in the model, the road network, and the network of the scheduled services. Those are modeled in different ways, which will be described in Section 3.4. The inputs for the road network are the distance between the nodes. The road network can be used by empty and loaded trucks. The information on the network of scheduled services is based on the scheduled services available.

Containers

Containers in the model can use the scheduled services and the trucks to travel over the arcs. Each container is routed individually and requires an origin, destination, a start time, and a due date. The containers can travel to all nodes but is not able to travel back over the same arc, so loops can be prevented. This decreases the calculation options for the models.

When a container is introduced in the network and has arrived at a node, the time between the delivery and the pickup at the node is the waiting time.

Trucks

Trucks in the model are able to drive through the network and can visit nodes multiple times. The truck routing is a Multi-D&T VRPTW-R problem based on the model of [51] and the constraints to be able to be loaded and transporting containers are added.

A truck can use the road network and travel between all nodes with a road. Trucks have an origin, a destination, a start time and a end time of operation, and a limited set of moves. The operational time corresponds in real life to the time that a truck is ready to drive, so there is a truck and a driver available. A move is defined as passing an arc and counted for all nodes a truck visits. The number of moves is introduced so the truck can be individually tracked and visit nodes multiple times. The time between the start time and the end time is seen as the active time where the truck can either be used to drive through the network or remain parked at the depot. Both models only use the trucks needed and the trucks which do not have to transport a container, stay at the origin and are not included in the total costs. The time before the truck leaves the depot and after the truck arrives back at the depot counts as the operational time. The trucks have an estimated velocity, cost per hour of usage, and cost per kilometer of driving. There is no difference in empty driving and loaded driving when considering the costs, which is an assumption that could be altered in future research.

Scheduled services: Trains and ships

The trains and the ships in the model have fixed departure times, transport times, and costs. Dependent on the kilometers of the service in combination with the mode (train or ship), the costs per kilometer and travel time are estimated. The trains and ships have an associated limited capacity.

3.2.2. Objective function

The objective of the model is to minimize the total costs of the transport, considering the usage of the scheduled services paid per container, the waiting time of containers at nodes and the costs of driving the trucks (which can be divided into time costs and distance costs).

3.2.3. Outputs of the model

The outputs of the model are determined by the minimization of the objective function based on costs. The output of the model contains the optimal route of the truck and the container based on costs. With these outputs, the KPIs can be analysed.

Containers

The outputs for the containers are the optimal routes where the costs for the entire system are optimal. Based on the optimal route, the modal split can be calculated. We define modal split as the percentages of kilometers a certain mode is used out of the total distance the containers are transported.

Trucks

The outputs of the truck is the optimal route (and time) of the truck to pickup and deliver all the containers. The route of the truck is not only considered between the pickup and delivery location, but also the empty moves. Based on this information, the loaded to empty rate (effective ratio) is determined.

Costs

Minimizing the total cost of the model is the objective function of the model. The costs are indicated for all modes. The truck costs include the costs of the distance driven of the truck and the time costs from the moment it leaves the depot until it arrives at the depot. The costs of the scheduled services are estimated based on the costs per container per trip (considering the distance), which is different for both the modes. The waiting time of the containers at nodes is also included.

CO_2 emissions

Based on the driven distances and the amount of CO_2 emitted by the modes in Tonne/TEU-km the amount of CO_2 emissions of the transport can be determined. The changes in CO_2 emissions are indirect effect of planning container and truck routes together, because it is not considered in the objective function of both models.

3.3. Mathematical model

In this section the mathematical formulation of the ICTR model and the benchmark model are introduced. By first, showing the sets and indices used for the model. Secondly, by formulating the objective function and the constraints of the ICTR model. Finally, by mathematically formulating the benchmark model.

3.3.1. Sets and indices

Notations	
Indices and sets	
T	set of trucks indexed by t
M	set of moves of a truck indexed by m
N	set of nodes in the network indexed by i and j
A	set of scheduled services indexed by a
K	set of containers indexed by k
Parameters	
(o_k, d_k)	the origin and final destination of container k
(o_t, d_t)	the origin and final destination of truck t
(m_0, m_f)	move 0 and final move
(r_k, q_k)	the operational with the beginning and end of container k
(r_t, q_t)	the start time and end time of the operational time of truck t
σ_{ij}	travel time by road from node i to node j (including loading and unloading)
l_a	departure time for scheduled service a
v_a	travel time for service a
(s_a, t_a)	starting point of service a and destination of service a
u_a	container capacity of a service
c_a	the costs of using service a
f_{ij}	the travel distance costs by truck from node i to node j
b_i	waiting costs of a container at node i
e^t	truck costs per unit time (driver costs)
Decision variables	
z_a^k	binary, 1 if container k is using service a, zero otherwise
z_{ij}^k	binary, 1 if container travels from i to j by a truck over a road, zero otherwise
$x_{ij}^{t,m}$	binary, 1 if truck t is moving from i to j in move m, zero otherwise
$y_{ij}^{k,t,m}$	binary, 1 if truck t in move m is transporting container k, zero otherwise
ρ_i^k	the time that container k arrives at node i
ξ_i^k	the time that container k leaves node i
$\tau_i^{t,m}$	the time that truck t in move m arrives at node i
ϕ^t	the time that truck t leaves the origin
w_i^k	waiting time of container k at node i
M	a sufficiently large positive number

3.4. ICTR Model

Objective function

$$\min \sum_{k\in K}\Big(\sum_{a\in A} c_a z_a^k + \sum_{i\in N} w_i^k b_i\Big) + \sum_{t\in T}\sum_{i\in N}\Big((\tau_i^{t,m_f} - \phi^t)e^t + \sum_{m\in M}\sum_{j\in N} x_{ij}^{t,m} f_{ij}\Big) \tag{3.1}$$

Objective function [3.1] is minimizing the total costs of the transport by determining the optimal route for individual trucks and containers through the network. The costs of the container transport are determined by the costs when the container uses a scheduled service (by $\sum_{a\in A} c_a z_a^k$), the waiting time at each depot (by $\sum_{i\in N} w_i^k b_i$). The costs of the truck are determined by the time spent by each truck (labour costs), and the driving costs (costs of fuel). The truck distance used is the total distance of a truck loaded and empty and the time of the truck is the time from where it leaves the depot to when it arrives back to the depot (operational time). In the remainder of this section, the constraints of the ICTR model are provided in different groups.

Container routing

The container routes are constrained by [3.2],[3.3],[3.4],[3.5] and [3.6].

Constraint [3.2] ensures that all containers leave the origin and arrive at a node by truck ($\sum_{i\in N} z_{o_k,i}^k$) or by scheduled service ($\sum_{a\in A:s_a=o_k} z_a^k$). Constraint [3.3] ensures that all containers arrive by a truck ($\sum_{i\in N} z_{i,d_k}^k$) or a scheduled service ($\sum_{a\in A:t_a=d_k} z_a^k$) at the final destination of the container.
Constraint [3.4] is a flow conservation equation which ensures that if a container arrives at a node by truck or by a scheduled service, it leaves that node by a truck or a scheduled service (unless the node is the origin or the destination of the container, then constraints [3.2] or [3.3] apply).
Constraint [3.5] ensures that all nodes can be visited once by a container prevents the container from making loops. Constraint [3.6] prevents the container to return at a node where it has been before. The constraints state that for all containers and nodes the containers only use an arc (by road or by scheduled service) once.

$$\sum_{i\in N} z_{o_k,i}^k + \sum_{a\in A:s_a=o_k} z_a^k = 1 \quad \forall\, k\in K \tag{3.2}$$

$$\sum_{i\in N} z_{i,d_k}^k + \sum_{a\in A:t_a=d_k} z_a^k = 1 \quad \forall\, k\in K \tag{3.3}$$

$$\sum_{j\in N} z_{ji}^k + \sum_{a\in A:t_a=i} z_a^k = \sum_{j\in N} z_{ij}^k + \sum_{a\in A:s_a=i} z_a^k \quad \forall\, k\in K,\ i\in N\setminus\{o_k,d_k\} \tag{3.4}$$

$$\sum_{a\in A:t_a=i} z_a^k + \sum_{j\in N} z_{ji}^k \le 1 \quad \forall k\in K, i\in N \tag{3.5}$$

$$z_{ij}^k + z_{ji}^k + \sum_{a\in A:(t_a=i\ \&\ s_a=j)} z_a^k + \sum_{a\in A:(t_a=j\ \&\ s_a=i)} z_a^k \le 1\ \forall\ k\in K, i\in N, j\in N \tag{3.6}$$

Truck routing

The routing of the trucks is bounded by constraints [3.7],[3.8] and [3.9]. Constraints [3.7] and [3.8] ensure that for all trucks, the moment that the truck has to leave the origin to transport a container, there is a pickup point and a delivery point. [3.7] bounds the pickup and delivery point for every truck and bounds the number of trucks departing. [3.8] bounds for every truck the departing value in such a way that there is only a truck used when a container has to be transported, otherwise the truck will not leave the origin.
Constraint [3.9] is the flow conservation constraint. The trucks which arrive at a node will leave that node, for all trucks, in all moves (except the last move) at all nodes.

$$\sum_{i\in N} x_{o_t,i}^{t,m_0} = \sum_{i\in N} x_{i,d_k}^{t,m_f} \le 1 \ \ \forall\ t\in T \tag{3.7}$$

$$\sum_{i\in N} x_{o_t,i}^{t,m_0} = \sum_{i\in N}\sum_{j\in N} x_{ij}^{t,m_0} \quad \forall\ t\in T \tag{3.8}$$

$$x_{i,i}^{t,m} + \sum_{j\in N\setminus i} x_{ji}^{t,m} = x_{i,i}^{t,m+1} + \sum_{j\in N\setminus i} x_{ij}^{t,m+1} \quad \forall\ t\in T, m\in M\setminus m_f, i\in N \tag{3.9}$$

Routing of the schedules services

The scheduled services are bounded by constraint [3.10] which ensures that the number of containers transported by a scheduled service cannot exceed the maximum capacity of that scheduled service.

$$\sum_{k \in K} z_a^k \leq u_a \quad \forall\ a \in A \tag{3.10}$$

Combining container and truck routing

The individual containers and the individual trucks are combined by constraints [3.11] and [3.12].
Constraint [3.11] links the truck, move and location of the truck to the loaded moves of the truck.
Constraint [3.12] links the loaded move of a truck to a container.

$$x_{ij}^{t,m} \geq \sum_{k \in K} y_{ij}^{k,t,m} \quad \forall t \in T, m \in M, i \in N, j \in N \tag{3.11}$$

$$z_{ij}^k = \sum_{t \in T} \sum_{m \in M} y_{ij}^{k,t,m} \quad \forall k \in K, i \in N, j \in N \tag{3.12}$$

Time of trucks

The time that trucks arrive at a node is constrained by [3.13],[3.14],[3.15] and [3.16].

Constraint [3.13] ensures that for all trucks, moves, and nodes the time of a truck in move m (except for m_0) is greater or equal than the time a truck arrives at the last node plus the travel time which includes loading time and unloading time if the truck is travelling from i to j.
Constraint [3.14] constraints the time for the first move (m_0). With ϕ_t as the departure time of truck t at the origin.
Constraint [3.15] ensures that the arrival time of the truck cannot exceed the final arrival time (q_t) of that truck in the final move.
Constraint [3.16] ensures that the truck leaves the first node after the start time of that truck (r_t).

$$\tau_j^{t,m} \geq \tau_i^{t,m-1} + \sigma_{ij} x_{ij}^{t,m} \quad \forall\ i \in\ N,\ j \in\ N,\ t \in\ T,\ m \in\ M \setminus m_0 \tag{3.13}$$

$$\tau_j^{t,m_0} \geq \phi^t + \sigma_{ij} x_{ij}^{t,m_0} \quad \forall\ i \in\ N,\ j \in\ N,\ t \in\ T \tag{3.14}$$

$$\tau_{d_t}^{t,m_f} \leq\ q_t \quad \forall\ t \in\ T \tag{3.15}$$

$$\phi^t \geq\ r_t \quad \forall\ t \in\ T \tag{3.16}$$

Arrival and departure time of containers at nodes

The time that containers arrive and leave at a node are bounded by the following constraints, [3.17],[3.18],[3.19], [3.20],[3.21],[3.22], [3.23], [3.24],[3.25],[3.26],[3.27],[3.29],[3.30]. This section introduces the big M. The parameter M is a large number that makes the constraints inactive when appropriate.

Arrival time at nodes for containers

Constraint [3.17] and constraint [3.18], set the boundaries for the time of the container in the scenario it is transported by a specific truck in a specific move. The constraint ensures that if the container has arrived by truck, the arrival time of the truck applies to the arrival time of the container, and if this is not the scenario (which means that the container did not arrive at node i by a loaded truck t at move m), the time is not bounded.

Constraint [3.19] and constraint [3.20], set the boundaries for the time of the container in the scenario it is transported by scheduled services. Where the l_a is the departure time of service a and the v_a the travel time when using the scheduled service. The goal of the 2 formulas is that the time that container k arrives at node i by a scheduled service is equal to the time when it left a node plus the time required to travel by scheduled service to node i.

Constraint [3.21] ensures that if the container is using a scheduled service, the container should arrive at the node before the pickup time at a node where it is transported from, and there is no scheduled service used, this restriction is removed by the Big M. If container k is arriving at node i with scheduled service a (which has the destination of i) the container should be available at the pickup point at the time before the cut-off time.

$$\rho_i^k \geq \tau_i^{t,m} - M(1 - y_{ji}^{k,t,m}) \quad \forall k \in K, t \in T, m \in M, i \in N, j \in N \tag{3.17}$$

$$\rho_i^k \leq \tau_i^{t,m} + M(1 - y_{ji}^{k,t,m}) \quad \forall k \in K, t \in T, m \in M, i \in N, j \in N \tag{3.18}$$

$$\rho_i^k \geq l_a + v_a - M(1 - z_a^k) \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.19}$$

$$\rho_i^k \leq l_a + v_a + M(1 - z_a^k) \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.20}$$

$$\rho_i^k \leq l_a + M(1 - z_a^k) \quad \forall k \in K, i \in N, a \in A : s_a = i \tag{3.21}$$

Departure time at nodes for containers

Constraints [3.22], [3.23] and [3.24] ensure that the time that if container k leaves node j and arrives at node i by truck t in move m is equal to the departure time of the container from a specific node.

Constraint [3.22] bounds the value of the departure time at the node of a truck has to be greater or equal than the time value of the arrival time of a truck if that truck is used to transport the container to the node (so $y_{ij}^{k,t,m}$ should be 1), and if this is not the case, the truck has no extra boundary. Constraint [3.23] and [3.24] bounds the departure time of a container to the particular truck it is using.

Constraints [3.25] and [3.26] ensure that the departure time of a specific container at a specific node is equal to the departure time of the used scheduled service or is not bounded. [3.25] ensures also that ξ_i^k has a positive value.

Constraints [3.27] and [3.28] ensures that the difference between the arrival and departure time is a positive value (the truck arrives before it leaves) and that the time between is the waiting time of the truck.

Constraints [3.29] and [3.30], set the boundaries for the time of the container for the departure time at the origin and the arrival time at the final destination of the container.

$$\xi_i^k \geq \tau_i^{t,m-1} - M(1 - y_{ij}^{k,t,m}) \quad \forall k \in K, t \in T, m \in M \setminus m_0, i \in N, j \in N \tag{3.22}$$

$$\xi_i^k \geq \tau_j^{t,m} - \sigma_{ij} - M(1 - y_{ij}^{k,t,m}) \quad \forall k \in K, t \in T, m \in M, i \in N, j \in N \tag{3.23}$$

$$\xi_i^k \leq \tau_j^{t,m} - \sigma_{ij} + M(1 - y_{ij}^{k,t,m}) \quad \forall k \in K, t \in T, m \in M, i \in N, j \in N \tag{3.24}$$

$$\xi_i^k \geq l_a z_a^k \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.25}$$

$$\xi_i^k \leq l_a + M(1 - z_a^k) \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.26}$$

$$\xi_i^k = w_i^k + \rho_i^k \quad \forall i \in N, k \in K \tag{3.27}$$

$$w_i^k \geq 0 \quad \forall i \in N, k \in K \tag{3.28}$$

$$\rho_{d_k}^k \leq q_k \ \forall \ k \in K \tag{3.29}$$

$$\xi_{o_k}^k \geq r_k \ \forall \ k \in K \tag{3.30}$$

Binary variables

The binary decision variables are defined in constraints [3.31], [3.32], [3.33], and [3.34].

$$z_a^k \in \{0,1\} \quad \forall k \in K, a \in A \tag{3.31}$$

$$z_{ij}^k \in \{0,1\} \quad \forall k \in K, i \in N, j \in N \tag{3.32}$$

$$x_{ij}^{t,m} \in \{0,1\} \quad \forall t \in T, m \in M, i \in N, j \in N \tag{3.33}$$

$$y_{ij}^{k,t,m} \in \{0,1\} \quad \forall k \in K, t \in T, m \in M, i \in N, j \in N \tag{3.34}$$

3.5. Benchmark model

The benchmark model represents the current practice in the synchromodal transport models. Existing models in the literature (Chapter 1.3) consider, when routing individual containers, that for road transport the trucks are always and infinitely available. The benchmark first determines the route of the containers in Stage 1, considering that the trucks are always instantly available. This route is the input for Stage 2 of the benchmark, which determines the optimal route for the trucks to meet the demands of the route of the containers. This means that the optimization of the trucks is not integrated as in the ICTR model.

This interaction between different stages of the benchmark model is presented in Table 3.1. In Stage 1, the constraints for the routing of the container, the routing of the scheduled services, Container arrival and departure times - Create road time and the Binary variables - container and truck are implemented. There is one new formula, which creates time in the mode choice to use a truck. Constraint 3.42 creates time for the usage of trucks by including the time to travel by road from node i to node j to the arrival time at j for all containers, at all departure and arrival nodes.

Stage 2 determines the route of the truck considering the route of the container and the specific times of containers and trucks at all nodes.

Table 3.1: Overview of the formula modules applied in the benchmark (with Stage 1 and Stage 2) and the ICTR model

Modules	Stage 1	Stage 2	ICTR
Container routing	x		x
Truck routing		x	x
Routing of the scheduled services	x		x
Combining container and truck routing		x	x
Time of trucks		x	x
Container arrival and departure times - scheduled services	x	x	x
Container arrival and departure times - Create road time	**x**		
Container arrival and departure times - Trucks		x	x
Binary variables - Containers	x	x	x
Binary variables - Combining container and truck		x	x

3.5.1. Stage 1

Objective function of Stage 1

$$\min \sum_{k \in K} \Big(\sum_{a \in A} c_a \, z_a^k + \sum_{i \in N} w_i^k b_i + \sum_{i \in N} \sum_{j \in N} z_{ij}^k f_{ij} \Big) \tag{3.35}$$

The objective function of Stage 1 considers the costs of using a scheduled service, the waiting time and the costs of using a road segment for a container.

Routing of the containers

This part sets the route of the container though the network the following optimization problem:

$$\sum_{i\in N} z^k_{o_k,i} + \sum_{a\in A:s_a=o_k} z^k_a = 1 \quad \forall\ k \in\ K \tag{3.36}$$

$$\sum_{i\in N} z^k_{i,d_k} + \sum_{a\in A:t_a=d_k} z^k_a = 1 \quad \forall\ k \in\ K \tag{3.37}$$

$$\sum_{j\in N} z^k_{ji} + \sum_{a\in A:t_a=i} z^k_a = \sum_{j\in N} z^k_{ij} + \sum_{a\in A:s_a=i} z^k_a \quad \forall\ k \in\ K,\ i \in\ N \setminus \{o_k, d_k\} \tag{3.38}$$

$$\sum_{a\in A:t_a=i} z^k_a + \sum_{j\in N} z^k_{ji} \leq 1 \quad \forall k \in K, i \in N \tag{3.39}$$

$$z^k_{ij} + z^k_{ji} + \sum_{a\in A:(t_a=i\ \&\ s_a=j)} z^k_a + \sum_{a\in A:(t_a=j\ \&\ s_a=i)} z^k_a \leq 1\ \forall\ k \in K, i \in N, j \in N \tag{3.40}$$

Routing of the scheduled services

$$\sum_{k\in K} z^k_a \leq u_a \quad \forall\ a \in A \tag{3.41}$$

Time section

Arrival time at nodes

$$\rho^k_j \geq \sigma_{ij} + \xi^k_i - M(1 - z^k_{ij}) \quad \forall k \in K, i \in N, j \in N \tag{3.42}$$

$$\rho^k_i \geq l_a + v_a - M(1 - z^k_a) \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.43}$$

$$\rho^k_i \leq l_a + v_a + M(1 - z^k_a) \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.44}$$

$$\rho^k_i \leq l_a + M(1 - z^k_a) \quad \forall k \in K, i \in N, a \in A : s_a = i, \tag{3.45}$$

Departure time at nodes

$$\xi^k_i \geq l_a z^k_a \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.46}$$

$$\xi^k_i \leq l_a + M(1 - z^k_a) \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.47}$$

$$w^k_i \geq 0 \quad \forall i \in N, k \in K \tag{3.48}$$

$$\rho^k_{d_k} \leq\ q_k\ \forall\ k \in\ K \tag{3.49}$$

$$\xi^k_{o_k} \geq\ r_k\ \ \forall\ k \in\ K \tag{3.50}$$

Binary variables

$$z^k_a \in \{0,1\} \quad \forall k \in K, a \in A \tag{3.51}$$

$$z^k_{ij} \in \{0,1\} \quad \forall k \in K, i \in N, j \in N \tag{3.52}$$

$$\xi^k_i = w^k_i + \rho^k_i \quad \forall i \in N, k \in K \tag{3.53}$$

3.5.2. Stage 2

Stage 2 routes the trucks optimally when the containers have to follow the routes defined in Stage 1. The input from Stage 1 is the route of the containers by road ($Z_i^k j$) and the route of the containers by scheduled service (Z_a^k)

Objective function

$$\min \sum_{k \in K} \Big(\sum_{a \in A} c_a \, z_a^k + \sum_{i \in N} w_i^k b_i \Big) + \sum_{t \in T} \sum_{i \in N} \Big(\tau_i^{t,m_f} e^t + \sum_{m \in M} \sum_{j \in N} x_{ij}^{t,m} f_{ij} \Big) \tag{3.54}$$

The objective function of Stage 2 is the same as the objective function of the ICTR model so the output can be compared.

Routing the trucks

$$\sum_{i \in N} x_{o_t,i}^{t,m_0} = \sum_{i \in N} x_{i,d_k}^{t,m_f} \leq 1 \quad \forall\, t \in T \tag{3.55}$$

$$\sum_{i \in N} x_{o_t,i}^{t,m_0} = \sum_{i \in N} \sum_{j \in N} x_{ij}^{t,m_0} \quad \forall\, t \in T \tag{3.56}$$

$$x_{i,i}^{t,m} + \sum_{j \in N \setminus i} x_{ji}^{t,m} = x_{i,i}^{t,m+1} + \sum_{j \in N \setminus i} x_{ij}^{t,m+1} \quad \forall\, t \in T, m \in M \setminus m_f, i \in N \tag{3.57}$$

Combining truck and container

$$x_{ij}^{t,m} \geq \sum_{k \in K} y_{ij}^{k,t,m} \quad \forall t \in T, m \in M, i \in N, j \in N \tag{3.58}$$

$$z_{ij}^k = \sum_{t \in T} \sum_{m \in M} y_{ij}^{k,t,m} \quad \forall k \in K, i \in N, j \in N \tag{3.59}$$

Truck time

$$\tau_j^{t,m} \geq \tau_i^{t,m-1} + \sigma_{ij} x_{ij}^{t,m} \quad \forall\, i \in N,\; j \in N,\; t \in T,\; m \in M \setminus m_0 \tag{3.60}$$

$$\tau_j^{t,m_0} \geq \phi^t + \sigma_{ij} x_{ij}^{t,m_0} \quad \forall\, i \in N,\; j \in N,\; t \in T \tag{3.61}$$

$$\tau_{d_t}^{t,m_f} \leq q_t \quad \forall\, t \in T \tag{3.62}$$

$$\phi^t \geq r_t \quad \forall\, t \in T \tag{3.63}$$

Container time when truck use

$$\rho_i^k \geq \tau_i^{t,m} - M(1 - y_{ji}^{k,t,m}) \quad \forall k \in K, t \in T, m \in M, i \in N, j \in N \tag{3.64}$$

$$\rho_i^k \leq \tau_i^{t,m} + M(1 - y_{ji}^{k,t,m}) \quad \forall k \in K, t \in T, m \in M, i \in N, j \in N \tag{3.65}$$

$$\rho_i^k \geq l_a + v_a - M(1 - z_a^k) \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.66}$$

$$\rho_i^k \leq l_a + v_a + M(1 - z_a^k) \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.67}$$

$$\rho_i^k \leq l_a + M(1 - z_a^k) \quad \forall k \in K, i \in N, a \in A : s_a = i, \tag{3.68}$$

Container departure times

$$\xi_i^k \geq l_a z_a^k \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.69}$$

$$\xi_i^k \leq l_a + M(1 - z_a^k) \quad \forall k \in K, i \in N, a \in A : t_a = i \tag{3.70}$$

$$\xi_i^k \geq \tau_i^{t,m-1} - M(1 - y_{ij}^{k,t,m}) \quad \forall k \in K, t \in T, m \in M \setminus m_0, i \in N, j \in N \tag{3.71}$$

$$\xi_i^k \geq \tau_j^{t,m} - \sigma_{ij} - M(1 - y_{ij}^{k,t,m}) \quad \forall k \in K, t \in T, m \in M, i \in N, j \in N \tag{3.72}$$

$$\xi_i^k \leq \tau_j^{t,m} - \sigma_{ij} + M(1 - y_{ij}^{k,t,m}) \quad \forall k \in K, t \in T, m \in M, i \in N, j \in N \tag{3.73}$$

Define waiting time

$$\xi_i^k = w_i^k + \rho_i^k \quad \forall i \in N, k \in K \tag{3.74}$$

Binary variables

$$w_i^k \geq 0 \quad \forall i \in N, k \in K \tag{3.75}$$

$$\rho_{d_k}^k \leq q_k \; \forall \; k \in K \tag{3.76}$$

$$\xi_{o_k}^k \geq r_k \; \forall \; k \in K \tag{3.77}$$

3.6. Summary

This chapter explains how the joint optimization model for containers and trucks through a synchromodal network can be developed. The existing models, which consider intermodal or synchromodal container transport assume that when trucks are used in the model, there are infinite trucks available at any time. Where as in reality, trucks have to depart and return to depots, drive to a pickup point and a delivery point, etc. This research is finding out what consequences that could have on the synchromodal transport.

To analyse the potential advantages of integrating the truck routing and the container routing in a synchromodal network, the Integrated Container and Truck Routing (ICTR) model and the benchmark model are created. Both are new models that are individually routing the trucks and the containers.

The models are static and deterministic models and have the inputs of the network, trucks, containers, and scheduled services. The objective to minimize the total costs considering the trucks (driving and time costs) and the container travel costs (costs of all container trips and the waiting time).

The benchmark is divided into two stages. Stage 1 determines the route of the containers, assuming that at all nodes there are infinite trucks available at any time. Stage 2 has to find the optimal truck route with the available trucks, based on the input of Stage 1, the route of the container. The output of the benchmark is a feasible solution for the ICTR mode, which could be used as a warm start when calculation time is a factor during the experiments in Chapter 4.

4

Numerical Experiments

This chapter firstly explains how the models are implemented in Section 4.1. Secondly, describes how the scenarios used for the experiments are defined in Section 4.2. In Section 4.3 the results of the models for the different scenarios are shown and evaluated. The last section summarizes the chapter and gives an answer to how the choice of model impacts the costs and amount of CO_2 emission. It also concludes the impact of the individual routing of container and truck on the modal split and the number of kilometers trucks drive empty.

4.1. Implementation of the models

The ICTR model and the benchmark model are two large Mixed-Integer problems. Such problems can be implemented by several programs. In this research, Matlab is chosen as the programming software with the extensions of Yalmip and with the solver of Gurobi. Yalmip is a toolbox for modeling and optimization in MATLAB [29]. It simplifies the process of using optimization as an engineering tool and brings state of the art solvers and methods to the MATLAB user, and delivers a general framework for control relevant optimization in MATLAB. The Gurobi optimizer is used because it one of the fastest solvers available for LP, QP, QCP, and MIP problems [8]. It works firstly, by first pre-solving the problem, as a step to reduce the size of the problem and tightens the formulation. Thereafter, the cutting planes idea is used, which removes undesirable fractional solutions by tightening the formulation. Finally, the problem is solved by branch and bound which runs in parallel.

To improve the total computation time, the benchmark method and ICTR are solved at the same time. The solution procedure is illustrated in Figure 4.1. On the left is the input of the system and on the right is the output of the system. The benchmark model is the part of the combined implementation that is solved first. The input is sent to Stage 1 which determines the optimal route without considering the trucks. If the route is feasible in Stage 1, this route is used as the input to Stage 2. If Stage 1 of the benchmark is infeasible, then Stage 2 and the ICTR model will be infeasible too. Stage 2 will be infeasible because it requires the output of Stage 1 as input. The ICTR model will be infeasible because the model has nearly all container routing constraints of Stage 1, but also the truck routing constraints to integrate the trucks.

Stage 2 of the benchmark model uses the container route of Stage 1 as input and determines the route for the trucks. If Stage 2 is feasible, then the outputs are the container and truck routes for the benchmark model. These routes can be used as a warm start for the ICTR model. If Stage 2 is infeasible, then there are no suitable options for the trucks to transport all containers in accordance with the routes determined in Stage 1. The output of the benchmark model will be only the route of the containers. In the case of the ICTR model, it tries to solve the model without a warm start from the benchmark model and may still find a feasible solution.

The benchmark model and the ICTR model increase significantly in size when the number of containers, moves, nodes, or trucks are growing. The benchmark model has a lot less variables dependent on each other, because of the decreased inter-dependency of the variables and will solve quicker than the ICTR model. The processing time of the models is the time where it is required to solve the problem to an optimality gap of 0%. If this is not achieved after two hours, the simulation is stopped and the best, known, feasible solution is reported together with the optimality gap. If there is a solution for the benchmark, it solves all problems quicker than the ICTR model. The ICTR model uses the output of the benchmark as the warm start which saves some time but does not enable ICTR to find an optimal outcome within 2 hours.

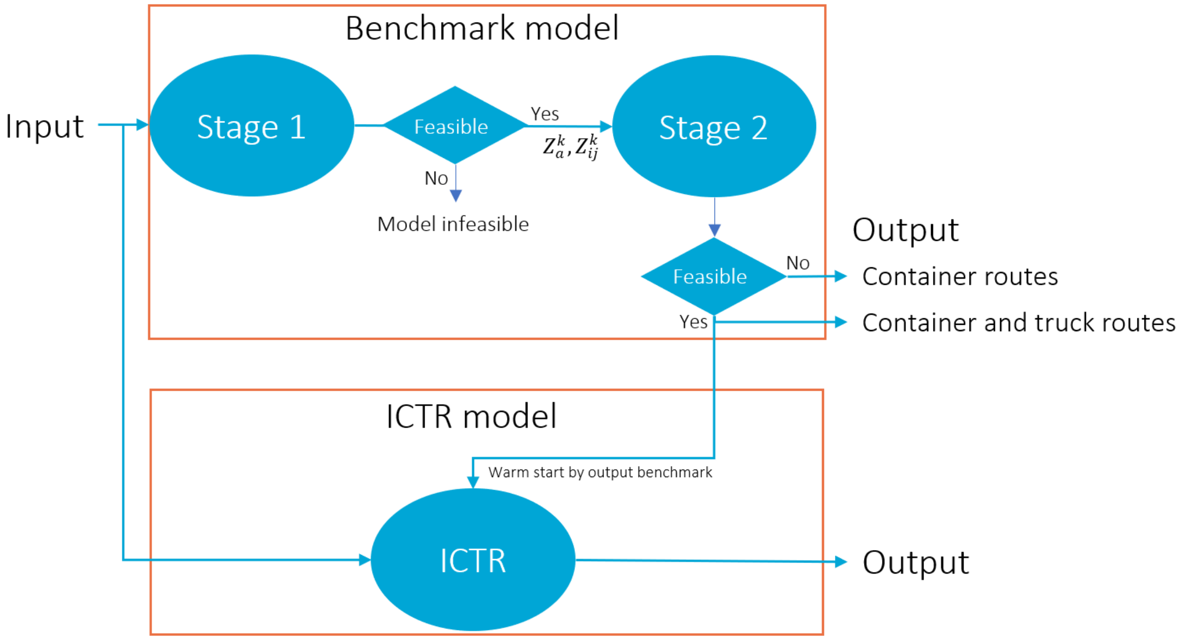

Figure 4.1: Solution strategy

4.2. Scenarios

To find out what the added value of the ICTR model could be, several scenarios are designed. In each scenario one parameter is changed such as; the network (number of nodes), containers, trucks (and moves), and the scheduled services. This results in eight different scenarios that are described in this section. The scenarios are used in the ICTR model and the benchmark model to find out what happens to the KPI and the routes of the trucks and the containers.

The first scenario is the base scenario where six containers travel from terminal to terminal in both export and import directions. This scenario is the starting point for other scenarios. The second scenario; the single truck scenario, has the same inputs as the base scenario, except for the number of trucks and the number of moves of the truck, and was considered to find out what the choices of the model will be when trucks are limited. Other scenarios focus on what influence one or Import and export of containers has on the result, what happens when there is an increased number of trucks, containers, and moves, what happens when the time windows are tightened for containers, what happens when the scheduled services are doubled and what choices the model makes when the network has increased in size.

4.2.1. Base scenario

The aim of the Base scenario is to set a starting point, where the other scenarios can be compared to. The Base scenario is a basic possible scenario where containers are travelling from several different terminals to other terminals in the network. The differences between the benchmark model and the ICTR model is expected to be visible in the results of this scenario. We expect a difference in the percentage of loaded kilometers of the trucks because driving with a truck is rather expensive if the whole route (from the starting point and the destination of the truck) is considered. This is taken into account in the container route choice for the integrated model, but not for the benchmark.

The input values, that are explained below (the network, the general inputs, the container, the truck, and the scheduled services) are used in the other scenarios as well. The input parameters of the base scenario and other scenarios are indicated in Table 4.4 accordingly.

Network

The network chosen is a synchromodal network based on the real hinterland transport network of the Port of Rotterdam from the Maasvlakte to Bad-Bentheim and Hengelo (See Figure 4.2). A synchromodal network can consist of multiple modes, in the hinterland of Rotterdam there is a water section and a rail section. In the network the modes of transport are represented based on the real world, by the water section from the open sea to the Maasvlakte and the rail section from the Maasvlakte to Bad-Bentheim. The network gives the model the option to choose the route of the container between scheduled services and truck, in combination with routing the trucks through the system. The network has multiple nodes, representing key locations and arcs representing transport connections by multiple modes. In the network there is also a highway crossing in at the location of Apeldoorn. This is a place where a container can be delivered and picked up. The node is included to increase the complexity and show the vehicle routing capability of the model. The trucks start and end at the truck company depots (Node 6 and Node 4) and are able to drive day and night.

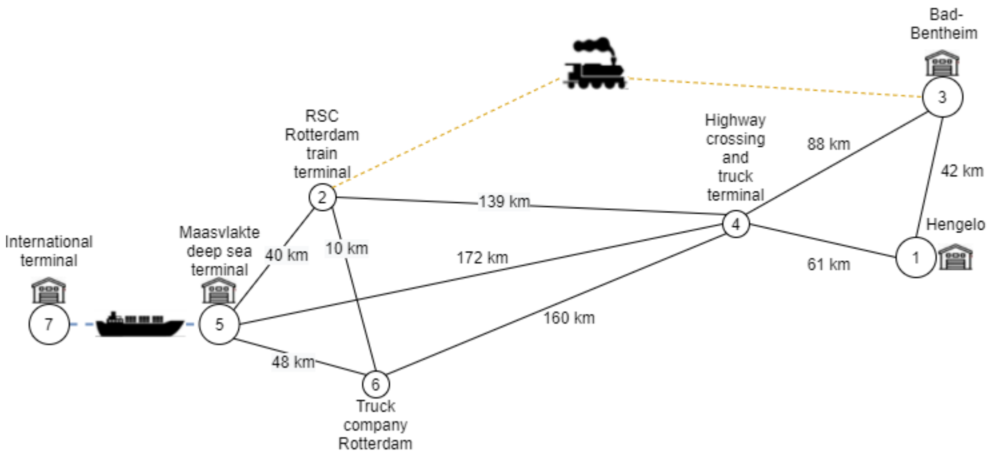

Figure 4.2: Network

The container terminals are at nodes 1, 3, 5, and 7. These are in real-life locations where containers can be stored, except for node 7. Node 7 is the moment that the container arrives in the dutch waters and enters the network from a container ship. In this network, the container terminals can be the origin and the destination of the containers. All nodes can be used for temporary storage and to switch in mode. The truck depot at node 6 is placed in the harbor of Rotterdam. The depot at node 4 is at Apeldoorn which is a place in the middle of the network, which is also the highway crossing.

The distances between the nodes are the real distances between the locations. For road transport it can be seen in Table 4.1, the distances for the scheduled services are 220 km between RSC Rotterdam and Bad-Bentheim and estimated as 75 km from the sea/international terminal to the Maasvlakte in Rotterdam.

Table 4.1: Road distances in the base scenario network between nodes in km

		Arrivals						
		1	2	3	4	5	6	7
Departures	1	-	-	42	61	-	-	-
	2	-	-	-	139	40	10	-
	3	42	-	-	88	-	-	-
	4	61	139	88	-	172	160	-
	5	-	40	-	172	-	48	-
	6	-	10	-	160	48	-	-
	7	-	-	-	-	-	-	-

Containers

The Base scenario contains six containers, with a variety of origins and destinations. They have two different starting points and three different destinations. The scenario has both import and export; there are containers travelling both towards and from the international shipping harbour. There are trips for containers that require a scheduled service and there are trips that can only be executed by truck.

It is chosen to have six containers in the base scenario because of the computation time and because when six containers are travelling through the network it remains possible to control the route of the containers by hand. Four containers are travelling from node 7. Two containers towards node 1 and two towards node 3. Node 1 and node 7 are the nodes furthest away from each other and most difficult to reach when considering intermodal transport (at least two truck trips, one ship trip and there is an option to use the train).

The containers travelling from node 7 to node 3 have to use at least two modes and are more likely to take the train towards node 3 then the containers towards node 1. The containers with as destination node 3, do not require an extra truck move. The containers with destination node 1 require a truck when it has been transported by a train service for the last move.

Next to the four containers travelling from node 7 towards the network, there are also two containers starting at node 3. Container 5 starts at node 3 and arrives at node 1, this is one road trip, which means the model does not need to make a mode choice. It is included because it is interesting how this booking is handled in the "priority list" of the trucks. Container 7 is travelling the other way compared to container 1 to 4 and is the only one with tight time windows. There are limited ships moving in the network which will be further explained in the scheduled service section, so the container should be in time at node 5 to be picked up by the ship.

General inputs

The time horizon for all scenarios is two days, and it is assumed that the trucks, containers, and scheduled services are transported during day and night. The two days are chosen because it is a reasonable time span for containers to travel through the hinterland network. The smaller setting gives more detail on the choices of the model in the scenarios, and show the route of a container and a truck individually.

Two days could be extended towards a longer horizon, such as a week or a month. The current time horizon is limited by the computational time, for instance, in the base scenario the computational time is more than two hours. An increased time horizon would result in a lot of extra computational time.

The costs and velocity of the modes are given in Table 4.2. The costs are based on [40] and the CO_2 emission in Tonne/TEU-km are determined using the method shown in the paper of Kim and Chang (2014)[22]. The costs of waiting is chosen to be €0.0005 per container per minute at every node. And the time costs of trucks drivers are estimated to be €0.05 per minute.

Table 4.2: Cost input of the model

Mode	Capacity	Variable cost TEU/hr	Velocity km/hr	costs tue/km	$CO2$ ton/tue-km
Ship	120	0,86	15	0,057	0,0016
Rail	60	15	73	0.205	0,0007
Truck	1	31	90	0,344	0,0019

Trucks

In the base scenario, five trucks with six moves are used. These numbers are chosen because it is possible for five trucks to transport the containers, the input remains controllable by hand, and because of the calculation time. The trucks in the network start and finish at the same node, this is chosen because at the end of the working day truck drivers want to be close to the depot. It is possible to have different starting and end locations. The operational/start time for trucks and the end of the operational time for trucks are not strictly bounded, the value of t=2000 is chosen as the time window of the truck. There are three trucks starting and finishing at node 6 and two trucks starting and finishing at node 4.

Scheduled services

There are two scheduled services, one from the international terminal to the Maasvlakte deep-sea terminal and one from the train terminal in Rotterdam to Bad-Bentheim. For all the scheduled services the following information is required: From which node the scheduled service departs and at which node it arrives.

Secondly at what time the scheduled service is departing and how long it takes to travel to the destination. Finally, the capacity and costs of using a scheduled service for an individual container are considered.

The train is driving in both directions, twice a day. So, when considering two days of modeling the trains have eight trips. The Ship is travelling once a day. The details can be found in Table 4.3.

Table 4.3: Scheduled services

Mode	Departure node	Arriving node	Departure time	Travel time	Capacity	Costs
Train	2	3	165	180	50	45
	3	2	525	180	50	45
	2	3	885	180	50	45
	3	2	1245	180	50	45
	2	3	1605	180	50	45
	3	2	1965	180	50	45
	2	3	2325	180	50	45
	3	2	2685	180	50	45
Ship	7	5	10	300	200	4,3
	5	7	600	300	200	4,3
	7	5	1450	300	200	4,3
	5	7	2040	300	200	4,3

4.2.2. Overview of the scenarios

The scenarios are chosen to illustrate what the difference is between the benchmark model and the ICTR model. This section contains general settings for the model and gives an overview of the input values used for the different scenarios. An overview of the scenarios and their input values can be found in Table 4.4, while their details are described in the following sections.

Table 4.4: Input values of the scenarios

	Network	Container				Truck					Scheduled
		#K	Origin	Destination	Release and Due date	#T	#M	Origin	Destination	Release and due date	
Base	Base	6	[7 7 7 7 3 3]	[3 3 1 1 1 7]	[1,2000]	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	Table 4.3
Single truck	Base	6	[7 7 7 7 3 3]	[3 3 1 1 1 7]	[1,2000]	**1**	**20**	**[4]**	**[4]**	[1,2000]	Table 4.3
Import only	Base	6	[**7 7 7 7 7 7**]	[**1 1 1 1 1 1**]	[1,2000]	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	Table 4.3
Import and export	Base	6	[**7 7 7 1 1 1**]	[**1 1 1 7 7 7**]	[1,2000]	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	Table 4.3
Increased containers and trucks	Base	**10**	[7 7 7 7 3 3 **7 1 3 3**]	[3 3 1 1 1 7 **1 7 7 7**]	[1,2000]	**6**	6	[4 4 **4** 6 6 6]	[4 4 **4** 6 6 6]	[1,2000]	Table 4.3
Tight time windows	Base	6	[7 7 7 7 3 3]	[3 3 1 1 1 7]	**Table 4.5**	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	Table 4.3
Doubled scheduled services	Base	6	[7 7 7 7 3 3]	[3 3 1 1 1 7]	[1,2000]	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	**Table 4.6**
Extended network	**Figure 4.3**	6	[7 7 7 7 3 3]	[3 3 1 1 1 7]	[1,2000]	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	**Table 4.8**

Single truck scenario

The single truck scenario is a scenario which simulates shortage of trucks. This is the most extreme scenario for when there are limited transport resources available. Input values for the truck are that the single truck starts and finishes at node 4 and has 20 moves to move the containers. The containers are booked in the same way for the single truck scenarios as the base scenario. Expected is that there will be significant differences between the benchmark (which assumes that trucks are always available) and the ICTR model, which includes the trucks in the routing process.

Import only

When there is one-way transport of multiple containers, there can be a shortage of trucks at certain locations. In this scenario there are six containers travelling from node 7 to node 1 and only five trucks to transport them through the network. All the other input values are the same as in the benchmark.

Import and export

In the import and export scenario, three containers are placed at both sides of the network (node 1 and node 7). This is the opposite to the Import scenario. Now the usage of trucks in a smart way can give benefits for the network. It is interesting to compare these results to the Import scenario, because the same number of kilometers are travelled by the containers but this time the trucks can be optimally used. Input values are except for the pickup and delivery node the same as the Base scenario.

Increased containers and trucks

The increased containers, trucks, and moves scenario increases the throughput of the network and this is expected to increase the calculation time. The aim of this scenario is to test the effectiveness of integrating trucks and container routing for increased throughput and what the limits of the model due to calculation time are.

The number of containers is increased to ten. There is one container travelling from node 7 to node 1 and one container from node 1 to node 7, this is through the network and requires at least two modes. There are two containers that are travelling from node 3 to node 7 which improves the balance between the import and the export.

Tight time windows

This the scenario where the containers have tightened time windows compared to the Base scenario. In the Base scenario, all time windows are within the two days, this scenario considers restrictions so there are less options available. Trucks in Stage 1 of the benchmark model are assumed unlimited and always available at every node. In real-life this is hardly the case, this scenario is expected to show that when integrating the trucks in the routing of the container, a problem which is infeasible in the benchmark will be feasible in the ICTR model. The input values are the same as for the Base scenario but with the time windows as shown in Table 4.5.

Table 4.5: Input of container in the tight time window scenario

Container	Pickup node	Delivery node	Departure time	Arrival time
1	7	3	5	1070
2	7	3	5	1070
3	7	1	5	1000
4	7	1	5	1120
5	3	1	60	120
6	3	7	160	2000

Containers 1,2,3 and 4 arrive in the network by the first ship from nodes 7 to 5, which means that they can not be earlier than t=310. The logical reachable train, if the train is used, is the train from node 2 to 3 departing at t=885. To reach node 2, four loaded truck moves are required that can be done by two trucks.

This means that containers 1,2,3 and 4 can reach node 1 within t=1070. From node 1, containers 3 and 4 have to be transported with one truck move from both to node 1.

Container 5, which is travelling from node 3 to 1, must be transported directly from the start of the simulation and requires one loaded truck move. Container 6 is the most difficult one, due to the schedule of the ship, this one has to reach node 5 before t=600.

Doubled scheduled services

The doubled scheduled services scenario doubles the number of scheduled services to find out what effect that has on the model. This means that the containers in the situation to take a train or ship will have a departure sooner available, which leads to decreased waiting times. The expected result of this change is that the benchmark model will route all containers through the same scheduled service (because there is no integration) and the integrated model will choose different departures to fit the truck limitations better.

In this scenario, the input values are the same as for the Base scenario but with doubled scheduled services. The extra departures are scheduled in between the departures from the Base scenario and has the same capacity and costs for containers. The new schedule is shown in Table 4.6.

Table 4.6: Doubled scheduled services

Mode	Departure node	Arriving node	Departure time	Travel time	Capacity	Costs
Train 1	2	3	165	180	50	45
	3	2	525	180	50	45
	2	3	885	180	50	45
	3	2	1245	180	50	45
	2	3	1605	180	50	45
	3	2	1965	180	50	45
	2	3	2325	180	50	45
	3	2	2685	180	50	45
Train 2	2	3	365	180	50	45
	3	2	725	180	50	45
	2	3	1085	180	50	45
	3	2	1445	180	50	45
	2	3	1805	180	50	45
	3	2	2165	180	50	45
	2	3	2525	180	50	45
Ship 1	7	5	10	300	200	4,3
	5	7	600	300	200	4,3
	7	5	1450	300	200	4,3
	5	7	2040	300	200	4,3
Ship 2	7	5	310	300	200	4,3
	5	7	900	300	200	4,3
	7	5	1750	300	200	4,3

Extended network

The Base scenario determines the optimal route for containers and trucks in a network of seven nodes. The question arises what would happen if the network size increases. The extended network thus models extra roads and extra scheduled services when considering the same input parameters for the containers and trucks as in the Base scenario. Due to the calculation time, the network is increased only by two nodes, the corresponding roads, and a shipping line. With this extension, the possible outcomes of increase in network size can be analyzed. The estimated result is that due to the extra nodes, which lead to extra transport options, the number of possibilities for the routing of containers and trucks increases, and this is expected to the benefits.

The extended network changes the Base network of seven nodes to a network with nine nodes, that can be seen in Figure 4.3. Nodes 8 and 9 are added, which have connections to the road network and to an added ship line that sails back and forth between node 8 and Hengelo with a stop around Nijmegen.

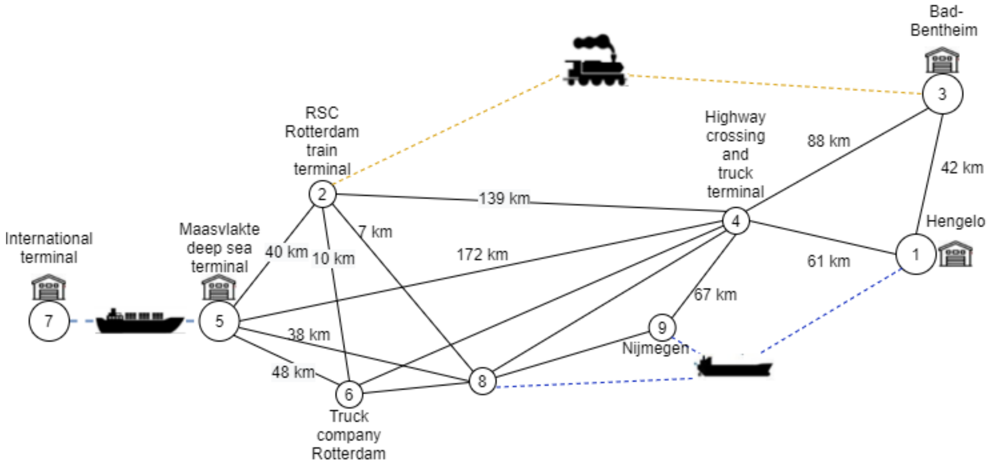

Figure 4.3: Extended network

Node 8 is a node in the center of the network and with a connection to nodes 2, 4, 5, 6, and 9. The network is connected between nodes 8 and 9 with a road and a scheduled service. Node 9 is a node located at Nijmegen and is connected to node 4 and 8 by road and to node 1 and 8 by ship. The distances between the nodes are estimated based on real distance data. The distance can be seen in Table 4.7.

Table 4.7: Travel distance between nodes of the truck network in kilometers

		Arrivals								
		1	2	3	4	5	6	7	8	9
Departures	1	-	-	42	61	-	-	-	-	-
	2	-	-	-	139	40	10	-	7	-
	3	42	-	-	88	-	-	-	-	-
	4	61	139	88	-	172	160	-	144	67
	5	-	40	-	172	-	48	-	38	-
	6	-	10	-	160	48	-	-	16	-
	7	-	-	-	-	-	-	-	-	-
	8	-	7	-	144	38	16	-	-	112
	9	-	-	-	67	-	-	-	112	-

The scheduled services in the extended network are the same as in the Base scenario, with the extension of ships 2 and 3, who are sailing between node 8 - 9 - 1 and node 1 - 9 - 8 can be seen in Table 4.8.

For the shipping line between node 8 - 9 - 1 and node 1 - 9 - 8, there are two ships sailing. One starting at node 1 with the departure time of 200, so containers released at an early time at node 1 or node 3 can use the ship. The ship is sailing in 480 minutes toward node 9 where it stops and has time to load and unload containers, before the ship continuous toward node 8 in 440 minutes. After node 8 the ship goes back with the same travel times as the other way towards node 9 and 1.

The other ship starts at node 8 at time 50, which means that only containers released early at node 5 can use this first services and is sailing with the same travel time between the nodes from nodes 8 - 9 - 1 and afterwards back to nodes 1 - 9 - 8.

Table 4.8: Scheduled services in the extended network

Mode	Departure node	Arriving node	Departure time	Travel time	Capacity	Costs
Train	2	3	165	180	50	45
	3	2	525	180	50	45
	2	3	885	180	50	45
	3	2	1245	180	50	45
	2	3	1605	180	50	45
	3	2	1965	180	50	45
	2	3	2325	180	50	45
	3	2	2685	180	50	45
Ship	7	5	10	300	200	4,3
	5	7	600	300	200	4,3
	7	5	1450	300	200	4,3
	5	7	2040	300	200	4,3
Ship 2	8	9	50	440	100	6,31
	9	1	550	480	100	6,88
	1	9	1100	480	100	6,88
	9	8	1600	440	100	6,31
Ship 3	1	9	200	480	100	6,88
	9	8	750	440	100	6,31
	8	9	1300	440	100	6,31
	9	1	1800	480	100	6,88

4.3. Results

In this section the results of the experiments are analysed by first showing KPIs achieved with the models at the different scenarios in Section 4.3.1, followed by an elaboration on the KPIs for the different scenarios. In Section 4.4 the differences between the scenarios are explained.

4.3.1. Result overview

Tables 4.9 and 4.10 show the results of the scenarios in costs, distance, modal split, truck distance, processing time and CO_2 emissions. These tables are explained here and the detailed information can be found in the following sections of the specific scenarios.

The costs are determined by a standard price in €/km for each mode and displayed for each mode and the waiting time. Significant improvement in costs can be made by integrating truck and container planning. The differences in costs are for the Base network mostly in truck costs and the train costs. The waiting time is also different, but it is only 0,1 % of the total costs. The difference in truck and train costs has the most influence on the results.

The distances in Table 4.9 and Table 4.10 are the distances travelled by the container in kilometers. For the trucks, these are the loaded kilometers. What in general can be seen is that there is no decrease in loaded truck kilometers, often an increase when ICTR is used instead of the benchmark. The ship kilometers are constant because the container has no other choice than to use the ship. The distance of the containers travelling by train does not increase in the ICTR model. The total distance of the travel of the containers decreases in nearly all scenarios. This happens due to the route choice of the model which minimizes the costs. For the chosen scenarios the optimal route of the container is always the route with the least distance. This does however not always have to be the case, if it would be cheaper to travel longer distances by a mode which costs less per kilometer then the optimal distance of the container will increase.

The modal split is determined by dividing the number of effective kilometers travelled by a particular mode to the total container transport distance. Based on the modal split, it is clear that there is no decrease in truck use for transport and often a decrease in train transport. It is important to mention that the modal split related considerations were not included in the objective function. For example, the share of train and ship could have been included in the objective to maximize their usage and the model then could have responded to that. This can be investigated as future work.

The truck distance results consider the loaded, empty, and total kilometers of the truck. A truck is creating value if it is driving with a container and losing value if it is driving empty. In Tables 4.9 and 4.10 it is clear that for all scenarios, when using the ICTR model compared to the benchmark model, most of the time there is a significant increase in effectiveness. The reason for this is explained by the route choice of the containers. In general, the trucks are relatively costly so improving the route and distance has a significant influence on the cost outcome of the model. Therefore, when the trucks are integrated into the routing process of the containers the model will try to route the trucks more reasonably and decrease the number of empty kilometers. It will be elaborated upon in the discussion of the results in Section 4.4.

The CO_2 emissions are estimated based on the value of the amount of CO_2 emissions in Tonne-TEU per kilometer, combined with the transported kilometers. Interesting to see is that, although it is not in the objective function of the models, the emissions decrease when the ICTR model is used (except for the doubled scheduled scenario), because the total travel distance is reduced the effective truck kilometers are increased. Even though the modal choice of trucks has increased, total CO_2 emission has decreased. The increase in CO_2 emission in the doubled schedule case can be explained by the costly waiting time for trucks at nodes, so it is more cost friendly to use a truck compared to other modes.

Table 4.9: Results of the scenarios (1)

Scenario		Base		Single truck		Import		Import and export		Incr. containers&trucks	
Model		Benchmark	ICTR	Benchmark	ICTR	Benchmark	ICTR	Benchmark	ICTR	Benchmark	ICTR
Costs (€)	Truck (empty and loaded)	562,2	474,6	485,1	419,2	Infeasible	777	932,5	732,9	1.232,0	1.056,0
	Ship	21,5	21,5	21,5	21,5	-	25,8	25,8	25,8	38,7	38,7
	Train	180	135	180	135	-	180	135	90	263,7	218,7
	Waiting costs	1	1,9	1,1	1,8	-	1,2	1	2,3	1,5	3,1
	Total	764,7	633,0(-17%)	687,7	577,5(-16%)	-	984,0(-%)	1.094,3	851,0(-22%)	1499	1276(-%15)
Container distance (km)	Truck	546	697	546	697	492	794	945	1096	1381	1531
	Ship	375	375	375	375	450	450	450	450	675	675
	Train	880	660	880	660	1320	880	660	440	1100	880
	Total	1801	1732(-4%)	1801	1732(-4%)	2262	2124(-%)	2055	1986(-3%)	3156	3086(-2%)
Modal split (%)	Truck	30%	40%	30%	40%	22%	37%	46%	55%	44%	50%
	Ship	21%	22%	21%	22%	20%	21%	22%	23%	21%	22%
	Train	49%	38%	49%	38%	58%	41%	32%	22%	35%	29%
Truck distance (km)	Loaded	546	697	546	697	-	794	945	1096	1381	1531
	Empty	629	389	580	353	-	848	1022	657	1381	1048
	Total	1175	1086(-8%)	1126	1050(-7%)	-	1642(-%)	1967	1753 (-11%)	2762	2579(-7%)
	Effective	46%	64%	48%	66%	-	48%	48%	63%	50%	59%
Processing (s)	Processing time	310	7200	52	7200	76	7200	601	7200	1080	7200
	optimality gap	0%	9%	0%	2%	Infeasible	12%	0%	39%	0%	38%
CO_2 emissions (ton)	total CO_2 ton of container travel)	3,45	3,13(-9%)	3,36	3,06(-9%)	-	4,46(-%)	4,92	4,36(-11%)	7,10	6,60(-7%)
	Truck	65%	66%	64%	65%	-	70%	76%	76%	74%	74%
	Ship	17%	19%	18%	20%	-	16%	15%	17%	16%	17%
	Train	18%	15%	18%	15%	-	14%	9%	7%	9%	9%

Table 4.10: Results of the scenarios (2)

Scenario		Base		Tight time windows		Doubled scheduled		Extended network	
Model		Benchmark	ICTR	Benchmark	ICTR	Benchmark	ICTR	Benchmark	ICTR
Costs (€)	Truck (empty and loaded)	562,2	474,6	482,9	482,9	570,4	457,5	487,7	487,7
	Ship	21,5	21,5	21,5	21,5	21,5	21,5	35,3	35,3
	Train	180	135	135	135	225	135	90	90
	Waiting costs	1	1,9	1	1	0,5	1,1	0,7	0,7
	Total	764,7	633,0(-17%)	640,4	640,4(-0%)	817,4	615,1(-25%)	613,7	613,7(-0%)
Container distance (km)	Truck	546	697	697	697	326	697	682	682
	Ship	375	375	375	375	375	375	525	525
	Train	880	660	660	660	1100	660	440	440
	Total	1801	1732(-4%)	1732	1732(-0%)	1801	1732(-4%)	1647	1647 (-0%)
Modal split (%)	Truck	30%	40%	40%	40%	18%	40%	41%	41%
	Ship	21%	22%	22%	22%	21%	22%	32%	32%
	Train	49%	38%	38%	38%	61%	38%	27%	27%
Truck distance (km)	Loaded	546	697	697	697	326	697	682	682
	Empty	629	389	389	389	496	371	471	471
	Total	1175	1086(-8%)	1086	1086(-0%)	822	1068(+30%)	1153	1153 (-0%)
	Effective	46%	64%	64%	64%	40%	65%	59%	59%
Processing (s)	Processing time	310	7200	53	7200	54	7200	185	7200
	optimality gap	0%	9%	0%	9%	0%	5%	0%	37%
CO_2 emissions (ton)	total CO_2 ton of container travel)	3,45	3,13(-9%)	3,13	3,13(-0%)	2,93	3,09(+5%)	3,35	3,35(-0%)
	Truck	65%	66%	66%	66%	53%	66%	65%	65%
	Ship	17%	19%	19%	19%	20%	19%	25%	25%
	Train	18%	15%	15%	15%	26%	15%	9%	9%

4.3.2. Base

When considering the results of Table 4.9 there are several differences between the route choices of the benchmark model and the ICTR model. The benchmark model determines the optimal route of the container without considering the optimal route of the truck. This results in different optimal solutions for the benchmark model and the ICTR model.

There is a significant improvement in the costs which decrease with 17 %, total container distance which decreases with 4 %, total truck distance decreases with 7 % and CO_2 emissions decrease with 2 %. The improvements when using the ICTR model compared to the benchmark model can be explained by the different routes of the containers.

Table 4.11 shows the route of the containers through the network, with for all containers the number of the specific container and the moves of the container where the first number is the departure node and the second number the node where the container arrives. The table contains the information of the route of all individual containers and shows if the container is travelling by truck (T) or by a scheduled service (S).

The benchmark model shows the expected result, which is that for containers with the same origin and destination the route is always the same because the availability of trucks is left out of the equation when the route of the container is determined. This results in the same route for containers 1 & 2 and containers 3 &4.

The ICTR model has found a better result by integrating the routing of the trucks and the containers. The difference in the routing can be seen in bold in the table. Container 3 chooses instead of taking the scheduled service from (2-3)S and Truck (3-1)T, to use the truck more. When only considering the costs when the trucks are loaded this would be a worse scenario (the transport by the truck is more expensive than using the train from node 2 to node 3).

The costs of the train and the costs of the truck, that can be explained by the different route choices the model has made. The ship costs are for both models the same, the reason for this is that when travelling from or to node 7 the only option is by ship, so the ship has a monopoly on the water segment. For the train and truck costs the specific route of the container is explained. Interesting to see is that the waiting time at the nodes has doubled.

Table 4.11: Route of the containers in the Base scenario with T=truck and S is scheduled service (train or ship)

Container	ICTR				Container	Benchmark			
1	(7-5)S	(5-2)T	(2-3)S		1	(7-5)S	(5-2)T	(2-3)S	
2	(7-5)S	(5-2)T	(2-3)S		2	(7-5)S	(5-2)T	(2-3)S	
3	(7-5)S	**(5-4)T**	**(4-1)T**		3	(7-5)S	(5-2)T	(2-3)S	(3-1)T
4	(7-5)S	(5-2)T	(2-3)S	(3-1)T	4	(7-5)S	(5-2)T	(2-3)S	(3-1)T
5	(3-1)T				5	(3-1)T			
6	(3-4)T	(4-5)T	(5-7)S		6	(3-4)T	(4-5)T	(5-7)S	

Table 4.12 shows the route of the truck from move to move. In bold are the moves in which the truck is transporting a specific container (given behind the move). What can directly be seen is that by optimally using the driving trucks, the number of trucks is reduced and the number of loaded trips per truck has increased.

In the benchmark model, truck 5 is not used and remains at its start location, the other trucks are driving to pick up and deliver two or three containers within the six moves of the trucks. The ICTR model requires three trucks to deliver the same number of containers. Due to the integration of the trucks and the container decisions, in this scenario moves which are not used in the Benchmark model (the first and the last) are used for transport. Now on average a truck is loaded three moves of six compared to two out of six for the benchmark model.

The ICTR sends truck 1 in moves 5 and 6 to pick up and deliver container 3 from node 5 to node 4. Truck 2 starts with driving in the first move at the time that it is loaded with container 3. The truck can wait for free because only the time that the trucks leave from the depot until the truck arrives back at the depot count towards the transport cost. Due to the integration, moves that can occasionally be used by the benchmark model (when the container is at the right time at the right place) can be planned by the ICTR model.

Table 4.12: Truck route for ICTR and Benchmark model with in bold the loaded moves and the containers which it transports

	ICTR					
	Move					
Truck	1	2	3	4	5	6
1	(4-3)	**(3-4) (K6)**	**(4-5) (K6)**	**(5-2) (K2)**	(2-5)	**(5-4) (K3)**
2	**(4-1) (K3)**	(1-3)	**(3-1) (K5)**	(1-3)	**(3-1) (K4)**	(1-4)
3	-	-	-	-	-	-
4	(6-5)	(5-5)	**(5-2) (K4)**	(2-5)	**(5-2) (K1)**	(2-6)
5	-	-	-	-	-	-
	Benchmark					
	Move					
Truck	1	2	3	4	5	6
1	(4-3)	**(3-1) (K4)**	(1-1)	(1-3)	**(3-1) (K3)**	(1-4)
2	(4-3)	(3-3)	**(3-1) (K5)**	(1-3)	**(3-4) (K6)**	(4-4)
3	(6-5)	**(5-2) (K2)**	(2-5)	**(5-2) (K1)**	(2-2)	(2-6)
4	(6-4)	**(4-5) (K6)**	**(5-2) (K4)**	(2-5)	**(5-2) (K3)**	(2-6)
5	-	-	-	-	-	-

The experiment with the Base scenario shows that there is a significant cost reduction when using the ICTR model because of the increase in effectiveness of trucks. By choosing the container routes optimally the trucks in the network can be used more effectively by increasing the number of effective kilometers.

4.3.3. Single truck

The single truck scenario has one truck to transport all containers over the roads. When comparing the results of the Single truck scenario to the Base scenario. The only difference in the container route choice compared to the base scenario is in the ICTR model, where containers 3 and 4 shifted the route which has no impact on the system. This is because the input values for both containers are the same and there is no cost difference in switching container 3 and 4. The fact that the ICTR model chooses the same route for the containers is interesting because of the change in the number of trucks. It can be explained by that the route of the base scenario is already optimal in effective truck kilometers and can be executed by a single truck. The container route in the benchmark model is the same for both scenarios, which is logical to choose because the benchmark does not consider the availability of trucks which is changed in this scenario.

The route of the single truck is given in 4.13. For both models the first ten moves are the same, both decide to transport container 6 first (before container 1-4 arrive at node 5), because it has to be in time for the ship from node 5 to 7. Followed by transporting the containers which have to be in time for the train. Finally, the models transport the last moves of the containers. It is clear that the trucks honor the time windows of the scheduled services and prioritize the containers which have to be in time. The improvements in the costs are due to the truck route of the single truck scenario. Which is compared to the base scenario with less moves from the depot and to the depot.

When considering a single truck, the expectation is that there could be time issues in the benchmark model when the container has to be in time for a scheduled service and there is limited capacity of truck available. This could not be confirmed by the single truck scenario, because there was enough time for the truck to travel twice (even three times) over the same road and deliver the container in time for the scheduled service. Interesting would be what happens in the single truck scenario if the time windows are tightened, so the truck demand at the same time increases to transport all the containers within the departure time and due date.

The improvements of the ICTR model compared to the benchmark in this scenario can be explained by that the ICTR optimally uses the movements of the truck across the network to assign containers. Whereas, the benchmark model does not consider those movements of the truck. This results in that the ICTR model requires less moves and less distance to transport all containers. The single truck scenario shows that the time windows of the scheduled services are limitations for the order of moves and that a single truck is able to transport all containers through the model.

When considering the KPI of the Single truck scenario, compared to the base scenario, the truck costs are significantly reduced. The total container distance is equal to the base scenario. Interestingly, the total truck distance has decreased for both models. This means that when using one truck with a lot of moves, the truck can have more effective kilometers. The explanation is the influence of the first and last trips of the truck, which are often empty.

Table 4.13: Single truck route, with in bold the loaded moves with the container indication behind and the underlined segments are the standstill moves

		ICTR							
Move									
1	2	3	4	5	6	7	8	9	10
(4-4)	(4-3)	**(3-4) (K6)**	**(4-5) (K6)**	**(5-2) (K1)**	(2-5)	**(5-2) (K2)**	(2-5)	**(5-2) (K3)**	(2-5)
11	12	13	14	15	16	17	18	19	20
(5-4) (K4)	**(4-1) (K4)**	(1-3)	**(3-1) (K5)**	(1-3)	(3-3)	**(3-1) (K3)**	(1-1)	(1-4)	(4-4)
		Benchmark							
Move									
1	2	3	4	5	6	7	8	9	10
(4-4)	(4-3)	**(3-4) (K6)**	**(4-5) (K6)**	**(5-2) (K1)**	(2-5)	**(5-2) (K2)**	(2-5)	**(5-2) (K4)**	(2-5)
11	12	13	14	15	16	17	18	19	20
(5-2) (K3)	(2-4)	(4-3)	**(3-1) (K5)**	(1-3)	(3-3)	**(3-1) (K3)**	(1-3)	**(3-1) (K4)**	(1-4)

4.3.4. Import only

The Import only scenario is only feasible when the ICTR model is used.The first stage of the benchmark model is feasible. The results in Table 4.9 show that the modal choice for containers of the benchmark is mostly on the usage of trains with 58%. Stage 2 of the benchmark is infeasible.

In Table 4.14 is the optimal choice of the route of containers of both the models displayed. The benchmark model chooses the same route for all the containers, because they have the same start and finish point and the truck availability is not considered. This becomes an issue when Stage 2 of the benchmark model is not able to find an optimal route for the trucks. Since only the second stage is infeasible, the truck capacity is the bottleneck. In such a scenario the bottleneck can be the number of moves, the number of trucks or the departure time of scheduled services. In this case the route determined by Stage 1 of the benchmark shows that the number of truck moves is the bottleneck.

The ICTR model is able to solve the scenario. What can be seen in Table 4.14 is that the choice of the route of the container is not the same for all containers although they have to travel between the same origin and destination. There are 4 containers travelling from node 7 to 5 to 2 to 3 and arrive at node 1 and there are two containers travelling from node 7 to 5 to 4 and arrive at 1. When considering the route of all the trucks in Table 4.15. There can be concluded that compared to the Base scenario all trucks are used and need at least five moves.

The ICTR model has compared to the base scenario a decrease in effective kilometers percentage. This can be explained by the one-way route of the containers which results in a lot of empty return trips. The driving from and the driving back to the depot has an influence on the result.

When comparing the benchmark to the ICTR model in the Import only scenario can be concluded that the ICTR model is able to solve the problem when there are limited trucks available where the benchmark is not able to. The reason for this is that the ICTR model is able to use the limited availability of trucks at certain locations optimally. Spending the limited moves of trucks effectively is important and can be the difference between feasible and infeasible.

Table 4.14: Container routes in the import only scenario

Container	ICTR				Container	Benchmark			
1	(7-5)S	(5-4)T	(4-1)T		1	(7-5)S	(5-2)T	(2-3)S	(3-1)T
2	(7-5)S	(5-2)T	(2-3)S	(3-1)T	2	(7-5)S	(5-2)T	(2-3)S	(3-1)T
3	(7-5)S	(5-2)T	(2-3)S	(3-1)T	3	(7-5)S	(5-2)T	(2-3)S	(3-1)T
4	(7-5)S	(5-2)T	(2-3)S	(3-1)T	4	(7-5)S	(5-2)T	(2-3)S	(3-1)T
5	(7-5)S	(5-4)T	(4-1)T		5	(7-5)S	(5-2)T	(2-3)S	(3-1)T
6	(7-5)S	(5-2)T	(2-3)S	(3-1)T	6	(7-5)S	(5-2)T	(2-3)S	(3-1)T

Table 4.15: Truck routes in the import only scenario for the ICTR model, the Benchmark model is infeasible

	ICTR					
	Move					
Truck	1	2	3	4	5	6
1	(4-1) (K1)	(1-3)	(3-1) (K2)	(1-3)	(3-1) (K6)	(1-4)
2	(4-1) (K5)	(1-3)	(3-1) (K3)	(1-3)	(3-1) (K4)	(1-4)
3	(6-5)	(5-4) (K5)	(4-5)	(5-2) (K6)	(2-6)	(6-6)
4	(6-5)	(5-5)	(5-4) (K1)	(4-5)	(5-2) (K4)	(2-6)
5	(6-5)	(5-5)	(5-2) (K3)	(2-5)	(5-2) (K2)	(2-6)

4.3.5. Import and export

The import and export scenario has three containers from node 7 to node 1 and three containers from node 1 to node 7. Due to the limited number of trucks compared to the number of containers, not all containers can be transported at the same time. There are a lot of similarities in the container route choice of both models, that can be seen in Table 4.16. For instance, the route of the containers travelling from node 1 to node 7, no containers use the train from node 1 to node 7 in both models. This is due the departure time of the ship from node 5 to node 7. If the containers use the earliest train from node 3 to node 2, the containers arrive to late for the ship. For the three containers travelling from node 7 to node 1 the models have chosen a different route for a container. Where the benchmark model chooses the same route for all three containers, the ICTR model chooses a different route for container 2. Container 2 is travelling by truck moves: (5-4) and (4-1). When considering the truck route choice of both models in Table 4.17, the ICTR model requires one truck less due to the more effective use of the trip from an to the truck deport. Because, in the ICTR model truck 1 is waiting on truck 2 to deliver container 2 to node 4. Which can also be seen in the output of the ICTR model of the base scenario.

Based on this scenario there can be concluded that compared to the import scenario there are more effective kilometers of the truck, because the truck has less empty return moves. There is a significant increase in truck costs due to the optimal routing of the containers. For both models the schedule of the scheduled service between 5 and 7 is tight for containers starting from node 1 or node 3, so the scheduled services between (3-2)S are not an option.

Table 4.16: Container route in the import and export scenario for the ICTR and Benchmark model

Container	ICTR				Container	Benchmark			
1	(7-5)S	(5-2)T	(2-3)S	(3-1)T	1	(7-5)S	(5-2)T	(2-3)S	(3-1)T
2	(7-5)S	(5-4)T	(4-1)T		2	(7-5)S	(5-2)T	(2-3)S	(3-1)T
3	(7-5)S	(5-2)T	(2-3)S	(3-1)T	3	(7-5)S	(5-2)T	(2-3)S	(3-1)T
4	(1-4)T	(4-5)T	(5-7)S		4	(1-4)T	(4-5)T	(5-7)S	
5	(1-4)T	(4-5)T	(5-7)S		5	(1-4)T	(4-5)T	(5-7)S	
6	(1-4)T	(4-5)T	(5-7)S		6	(1-4)T	(4-5)T	(5-7)S	

Table 4.17: Truck route in the import and export scenario for the ICTR and Benchmark model

	ICTR					
	Move					
Truck	1	2	3	4	5	6
1	**(4-1) (K2)**	(1-3)	**(3-1) (K3)**	(1-3)	**(3-1) (K1)**	(1-4)
2	(4-1)	**(1-4) (K4)**	(4-1)	**(1-4) (K6)**	**(4-5) (K6)**	**(5-4) (K2)**
3	(6-2)	(2-4)	**(4-5) (K4)**	**(5-2) (K3)**	(2-6)	(6-6)
4						
5	(6-4)	(4-1)	**(1-4) (K5)**	**(4-5) (K5)**	**(5-2) (K1)**	(2-6)
	Benchmark					
	Move					
Truck	1	2	3	4	5	6
1	(4-4)	(4-3)	**(3-1) (K1)**	(1-3)	**(3-1) (K3)**	(1-4)
2	(4-1)	**(1-4) (K6)**	(4-3)	**(3-1) (K2)**	(1-4)	(4-4)
3	(6-4)	(4-1)	**(1-4) (K4)**	**(4-5) (K5)**	**(5-2) (K3)**	(2-6)
4	(6-2)	(2-4)	(4-4)	**(4-5) (K6)**	**(5-2) (K1)**	(2-6)
5	(6-4)	(4-1)	**(1-4) (K5)**	**(4-5) (K4)**	**(5-2) (K2)**	(2-6)

4.3.6. Increased containers and trucks

The possible improvement compared to the other scenarios by increasing the demand in the network is dependent on the start and finish location of the containers and the trucks. This scenario adds four containers and one truck. In Table 4.18 the routes of all the containers can be seen. The ICTR takes one different decision for container 3 compared to the benchmark model. In Table 4.19 the routes of the trucks can be seen. The difference in container route choice of container 3 which is using two truck moves without using a train. This can be explained by truck 6 which has to travel node 4 as the last move towards the deport and container 4 is picked up by truck 1 which has to leave node 4.

The ICTR model route choice of container 3 is the same situation as for the base scenario. Where a truck starts later such that its first move can be used to transport a container. This time the benchmark has also found a solution where the first and last move are used.

When considering the results on the KPI of the model in Table 4.9, there can be concluded that the costs, container distance, truck distance, and the total CO_2 has decreased when the ICTR model is used. But it has decreased relatively less than in the base scenario. This results from the origin and destination chosen for the new containers. The added containers do not have the option to use the train from node 3 to 2 due to the departure time of the ship at 5.

In conclusion, increased containers and trucks can lead to improved KPIs, but it all depends on the origin and the destination of the added containers. In this scenario it is only possible to travel by road from 1 to 5 (the scheduled service between (3-2)S is not an option due to time considerations).

Table 4.18: Container route in the increased containers and trucks scenario

Container	ICTR				Container	Benchmark			
1	(7-5)S	(5-2)T	(2-3)S		1	(7-5)S	(5-2)T	(2-3)S	
2	(7-5)S	(5-2)T	(2-3)S		2	(7-5)S	(5-2)T	(2-3)S	
3	(7-5)S	(5-4)T	(4-1)T		3	(7-5)S	(5-2)T	(2-3)S	(3-1)T
4	(7-5)S	(5-2)T	(2-3)S	(3-1)T	4	(7-5)S	(5-2)T	(2-3)S	(3-1)T
5	(7-5)S	(5-2)T	(2-3)S	(3-1)T	5	(7-5)S	(5-2)T	(2-3)S	(3-1)T
6	(1-4)T	(4-5)T	(5-7)S		6	(1-4)T	(4-5)T	(5-7)S	
7	(3-4)T	(4-5)T	(5-7)S		7	(3-4)T	(4-5)T	(5-7)S	
8	(3-4)T	(4-5)T	(5-7)S		8	(3-4)T	(4-5)T	(5-7)S	
9	(3-4)T	(4-5)T	(5-7)S		9	(3-4)T	(4-5)T	(5-7)S	
10	(3-1)T				10	(3-1)T			

Table 4.19: Truck route in the increased containers and trucks scenario

	ICTR					
	Move					
Truck	1	2	3	4	5	6
1	**(4-1) (K3)**	(1-3)	**(3-1) (K4)**	(1-3)	**(3-1) (K5)**	(1-4)
2	(4-4)	(4-3)	**(3-1) (K10)**	(1-1)	**(1-4) (K6)**	(4-4)
3	(6-4)	(4-3)	**(3-4) (K7)**	**(4-5) (K9)**	**(5-2) (K1)**	(2-6)
4	(6-4)	**(4-5) (K6)**	**(5-2) (K2)**	(2-5)	**(5-2) (K4)**	(2-6)
5	(6-4)	(4-3)	**(3-4) (K9)**	**(4-5) (K7)**	**(5-2) (K5)**	(2-6)
6	(4-4)	(4-3)	**(3-4) (K8)**	**(4-5) (K8)**	(5-5)	**(5-4) (K3)**
	Benchmark					
Truck	1	2	3	4	5	6
1	(4-4)	(4-3)	**(3-1) (K3)**	(1-3)	**(3-1) (K4)**	(1-4)
2	**(4-5) (K6)**	**(5-2) (K4)**	(2-4)	(4-3)	**(3-1) (K5)**	(1-4)
3	(6-4)	(4-3)	**(3-4) (K8)**	**(4-5) (K9)**	**(5-2) (K1)**	(2-6)
4	(6-4)	**(4-5) (K7)**	**(5-2) (K2)**	(2-5)	**(5-2) (K3)**	(2-6)
5	(6-4)	(4-3)	**(3-4) (K9)**	**(4-5) (K8)**	**(5-2) (K5)**	(2-6)
6	(4-4)	(4-3)	**(3-4) (K7)**	(4-3)	**(3-1) (K10)**	**(1-4) (K6)**

4.3.7. Tight time windows

The tight time windows scenario does not have any improvement of the ICTR model compared to the benchmark model. This can also be seen in the routes of the containers in Table 4.20. This can be explained by the decrease in options for the trucks and containers to move due to the time windows. If there is only one option left where the trucks are not the limitations and then the result is the same both models.

When comparing the tight time windows scenario to the base scenario, the benchmark shows improvement and the ICTR model shows regression. The improvement of the benchmark model are due to the decrease in transport options, and the option left happens to be an improvement. The regression in the ICTR model are because the container has less feasible travel options for scheduled services and has to choose a truck on a specific moment. The ICTR model has a slight increase in costs that can be explained in using an extra truck due to the availability requirements (Table 4.21).

In this scenario the route options are limited by time windows in such a way that the optimal solution is not bounded by the availability of trucks in the container routing process. For other time windows of the containers this could be the case. Under different assumptions on the time windows this may be the case and can be further investigated.

Table 4.20: Container routes in the tight time windows scenario

Container	ICTR & Benchmark			
1	(7-5)S	(5-2)T	(2-3)S	
2	(7-5)S	(5-2)T	(2-3)S	
3	(7-5)S	(5-4)T	(4-1)T	
4	(7-5)S	(2-3)S	(5-2)T	(3-1)T
5	(3-1)T			
6	(3-4)T	(4-5)T	(5-7)S	

Table 4.21: Truck route in the tight time windows scenario

	ICTR & Benchmark					
	Move					
Truck	1	2	3	4	5	6
1	(4-3)	**(3-1) (K5)**	(1-3)	(3-3)	**(3-4) (K6)**	(4-4)
2	**(4-5) (K6)**	**(5-4) (K3)**	**(4-1) (K3)**	(1-3)	**(3-1) (K4)**	(1-4)
3						
4	(6-6)	(6-5)	(5-5)	**(5-2) (K4)**	(2-6)	(6-6)
5	(6-6)	(6-5)	**(5-2) (K1)**	(2-5)	**(5-2) (K2)**	(2-6)

4.3.8. Doubled scheduled services

When the scheduled services are doubled, there are more options for the containers to use scheduled services. The benchmark model and the ICTR model cope with this differently.

Stage 1 of the benchmark model determines the route for the container based on the situation that trucks are always available see Table 4.22. The use of scheduled services is cheaper than the use of trucks so the benchmark model routes as much as possible scheduled services. When the model has to choose between multiple scheduled services over the same arc, it chooses the one with the least transport time from the origin to the destination. Therefore the output from Stage 1 of the benchmark will be having less spare time to cope with possible truck limitations. This causes the second stage to have less options for the trucks to move all the containers in time for the scheduled services. In this scenario Stage 2 of the benchmark has found a way to deal with this (Table 4.23).

This scenario compared to all the other scenarios has the most relative costs benefits for the ICTR model compared to the benchmark model. The doubled scheduled services lead to increased total costs for the benchmark model, because of the departure times of the scheduled services. It, furthermore decreases the costs in the ICTR model compared to the base scenario, because there is an added scheduled service which now can be used to decrease the total travel time of both the trucks and the containers.

It is interesting to see that the total truck kilometers of the benchmark are lower than the ICTR model, but the trucks have higher costs, this is because of the truck waiting time at nodes. The travel time of all trucks in the ICTR model is 1802 min and in the benchmark 5752 min. When considering the driver costs of €0.05 per minute this results in truck time costs of €90,1 for the ICTR model and € 287,6 for the benchmark model.

It can be concluded that when there are upfront plans made for scheduled services truck availability could be an issue for the benchmark model, which will become more expensive or infeasible. The ICTR model profits from the increased availability of scheduled services, due to the increased departure times.

Table 4.22: Container route in the doubled scheduled service scenario

Container	ICTR				Container	Bench			
1	(7-5)S	(5-2)T	(2-3)S		1	(7-5)S	(5-2)T	(2-3)S	
2	(7-5)S	(5-2)T	(2-3)S		2	(7-5)S	(5-2)T	(2-3)S	
3	(7-5)S	(5-2)T	(2-3)S	(3-1)T	3	(7-5)S	(5-2)T	(2-3)S	(3-1)T
4	(7-5)S	(5-4)T	(4-1)T		4	(7-5)S	(5-2)T	(2-3)S	(3-1)T
5	(3-1)T				5	(3-1)T			
6	(3-4)T	(4-5)T	(5-7)S		6	(3-2)S	(2-5)T	(5-7)S	

Table 4.23: Truck route in the doubled scheduled service scenario

	ICTR					
	Move					
Truck	1	2	3	4	5	6
1	**(4-1) (K4)**	(1-3)	**(3-1) (K3)**	(1-3)	**(3-1) (K5)**	(1-4)
2	(4-3)	**(3-4) (K6)**	**(4-5) (K6)**	**(5-2) (K3)**	(2-5)	**(5-4) (K4)**
3						
4	(6-5)	**(5-2) (K2)**	(2-5)	**(5-2) (K1)**	(2-6)	(6-6)
5						
	Benchmark					
	Move					
Truck	1	2	3	4	5	6
1	(4-3)	**(3-1) (K3)**	(1-3)	(3-3)	**(3-1) (K4)**	(1-4)
2	(4-3)	**(3-1) (K5)**	(1-4)	(4-4)	(4-4)	(4-4)
3	(6-5)	**(5-2) (K4)**	(2-5)	**(5-2) (K2)**	(2-6)	(6-6)
4	(6-5)	**(5-2) (K3)**	**(2-5) (K6)**	**(5-2) (K1)**	(2-6)	(6-6)
5						

4.3.9. Extended network

When the network is extended, dependent on how the network has increased, the options for the transportation of the containers increase. The extended network scenario has an extra scheduled service, which is the cheapest way to transport from node 7 to node 1. By using the added ship, the number of required truck moves decreases, and the trucks are not the bottleneck of the system. The container and truck route determined by both models in the extended network is the same for both, this can be seen in Table 4.24. This can be explained that by adding the scheduled service, which has an optimal route for the containers. The trucks are not the bottleneck in the system and can be available at all nodes at any time.

Table 4.24: Container route in the extended network scenario

Container	ICTR				Container	Benchmark			
1	(7-5)S	(5-2)T	(2-3)S		1	(7-5)S	(5-2)T	(2-3)S	
2	(7-5)S	(5-2)T	(2-3)S		2	(7-5)S	(5-2)T	(2-3)S	
3	(7-5)S	(5-8)T	(8-9)T	(9-1)S	3	(7-5)S	(5-8)T	(8-9)T	(9-1)S
4	(7-5)S	(5-8)T	(8-9)T	(9-1)S	4	(7-5)S	(5-8)T	(8-9)T	(9-1)S
5	(3-1)T				5	(3-1)T			
6	(3-4)T	(4-5)T	(7-5)S		6	(3-4)T	(4-5)T	(7-5)S	

4.4. Evaluation of the KPIs

The improvement of the ICTR model compared to the benchmark is dependent on several factors. The most important one is if the trucks are the bottleneck in the system. When considering the values of the system, given in Table 4.9 and 4.10, Table 4.25 can be created. This table evaluates the differences between the benchmark and the ICTR model in costs, transport distance, total truck distance and the differences in total CO_2 emissions. It can be seen in this overview, that in nearly all scenarios there is a decrease in costs and total container transportation distance when the ICTR model is used. Although it is not considered explicitly in the objective function, there is a slight decrease in the CO_2 emissions.

The doubled scheduled services have the most improvement compared to the benchmark model, an improvement of 25% in costs. The explanation for this is twofold. Firstly, the benchmark model costs increase due to the scheduled services chosen by Stage 1 which chooses the first possible service without considering the availability of the trucks. When doubling the scheduled services, this results in less time to reach the departure time of the chosen scheduled service. If multiple containers are scheduled on the same service and there is less time to reach the departure time, this results in a peak demand for the trucks or an infeasible result. The second part of the explanation is that the ICTR model performs better than in the base scenario, it optimally uses the extra available scheduled services. The route of the containers and the trucks are the same for the ICTR model in the base scenario and the doubled scheduled services scenario, the difference is in the waiting time of trucks and containers. The model chooses a more efficient scheduled service which decreases the waiting time and the active time of the truck. The ICTR model decreased the costs when there are more scheduled services by choosing service that worked well with the truck routing instead of the tightest time window.

Table 4.25: Changes in KPIs when ICTR is used in percentage of the KPI obtained using the benchmark model

	Base	Single truck	Import only	Import and export	Increased containers and trucks	Tight time windows	Doubled scheduled services	Extended network
Decrease in costs	17%	16%	-	22%	15%	0%	25%	0%
Decrease in transport distance of containers	4%	4%	-	3%	2%	0%	4%	0%
Decrease in total truck distance	8%	7%	-	11%	7%	0%	-30%	0%
Decrease in CO_2 emissions	9%	9%	-	11%	7%	0%	-5%	0%

4.5. Summary

In this chapter, the scenarios are introduced to find out what kind of benefits there could be of using the ICTR model compared to the benchmark model. The implementation of the models is done in Matlab by using Gurobi and Yalmip. The benchmark model is solved faster compared to the ICTR model and is used as the warm start generator for the ICTR model in order to reduce the computational time.

The scenarios are introduced in reference to a base scenario by varying a parameter such as the number of trucks, the origin, and destination of the containers (import and export), the number of moves, the number of containers and trucks, tightening the time windows of the containers, doubling the scheduled services, and extending the network.

The results of the scenarios show that a significant cost and CO_2 emission reduction is possible, in some cases 25 % in costs and up to 11 % of CO_2. The most important reason for possible benefits is the availability of trucks. When the trucks are not the bottleneck (and can be seen as always available) for the chosen route of Stage 1 in the benchmark, then there is no benefit in using the ICTR model. But if there are limited trucks available, or there is cooperation required between trucks and containers to fulfill the demand the ICTR model has significant advantages. The benefits of using the ICTR model compared to the benchmark increase when there are more time restrictions. When trucks are not always available, or it has to be in time for the departure of scheduled services the profits increase.

5

Conclusion and Recommendations

This chapter answers the research question of Chapter 1 in the conclusion (Section 5.1) and gives recommendations for further research in Section 5.2.

5.1. Conclusion

This research evaluates the impact of combining truck and container routing through a synchromodal transportation network. First, the current routing models in the literature are analysed. Secondly, the key performance indicators in synchromodal container transport are determined. Thirdly, a joint optimization model is developed and compared to a benchmark model which is also developed in this thesis representing the current practice. Fourthly, several scenarios are designed to evaluate the performance of the joint optimization model (ICTR). Finally, the results of the experiments are evaluated based on the performance indicators, including the total costs and CO_2 emissions.

The current synchromodal models consider the modal choice for containers without the individual routing of trucks. In the case that trucks are not unlimited and at any time available at all nodes, but have a starting location, final location, and time windows, this may lead to routes that are difficult to satisfy for the trucks.

Using the developed the Integrated Container and Truck Routing model (ICTR) in a synchromodal transport network there can be up to 25 % cost reduction compared to the models that assume that trucks are always available. Furthermore, there is CO_2 emission reduction by improving the effectiveness of trucks. Additionally, the ICTR model is able to solve scenarios that can not be solved by the benchmark model.

The improvement of using the ICTR model depends on the availability of the trucks for the containers at the nodes. This is first determined by the starting and final location of the truck (the distance from where the depot is to the start of the first loaded move), secondly the network in question (where the scheduled services are and if the trucks the bottleneck), and thirdly the specifications of the demand of the containers.

In conclusion, the impact of combined transport of containers and truck transport can be a decrease up to 25% in costs and up to 11% in CO_2 emissions, but it is dependent on the location of the demand, the availability of trucks, and the cost parameters. If there are limited trucks available with limited time, the potential benefits increase.

5.2. Recommendations

There are several interesting future research directions possible: to make the model more realistic, to include different terms in the objective function such as CO_2 emissions, to find a road map to implementation and the development of solution methodologies for the proposed ICTR model.

To create a more realistic model there are several options for further research. Firstly, considering more realistic parameter choices, considering more realistic networks with more nodes and arcs, considering the limitations of using a deterministic model .

The parameters used in the model are based on literature and include various assumptions. Simulating with real-world parameters will result in a more realistic outcome. When considering the terminals, there are different handling times per terminal and different storage costs per terminal, in the current model they are assumed equal for all nodes.

Extending the network would increase the reality of the model. Now a small part of the hinterland network of Rotterdam is modeled. Extending the network towards the furthest point of the Rotterdam hinterland network would increase the reality. Furthermore, the total time of the system should be more than two days. It would be really interesting to see what would happen in the extended more realistic cases.

The containers in this report are assumed to be one TEU containers, in reality there are different types of containers transported. One TEU 20ft containers are used a lot but the two TEU (high cube 40ft containers) should be included as well. Further research should look into the different types of containers. Another interesting future research topic would be what influence the load of the container has on the travel. A container which is loaded to the max could be possible cheaper to transport by truck and train then by ship. For example, when the water level is to low, the number of containers which can be transported by ship, is weight dependent because of the draft of the ship.

When considering the trucks, the driver and the truck costs must be analysed. The hourly costs of the truck are now assumed to be a constant, while in real life drivers get paid more during some hours for instance when driving through the night or driving on Sundays. When considering the fuel costs, the trucks fuel consumption is depend on the type of the truck, and the activity of the truck (using less fuel when turned off when waiting and more in hilly areas). In the ICTR and the benchmark models the costs of a truck driving with a container and without is assumed to be the same. The difference in the truck cost when transporting a container and when the truck is empty should be applied in further research. Other truck information to consider is the hourly availability of trucks. Trucks are not able to drive for unlimited hours since drivers have obligatory rest times. This is possible to handle in the ICTR model if the rest-locations are known. There are different truck driver types, some drive for a day, others for a week before returning to their origin. The truck velocity is estimated on average 90 km/hr, this is not considering any uncertainties on the road.

The scheduled services (ship and train) in the ICTR and the benchmark model are assumed as fixed schedules with a departure time and an arriving time and standard costs. For the scheduled services in the models, there is a standard price set for a container using a service. In reality the costs dependent on the departure time (when there is more demand for a spot on a train or ship the price is likely to increase) and on the number of containers which are on a service (if it is full it is cheaper then when there is only one truck on a service). Furthermore, It would be also interesting to find out what would happen if the empty travels of scheduled services were included.

For the ship, the schedules are not always pre-scheduled. The departure time is dependent on the handling time at the terminals and is dependent on the number of containers which have to be transported. The travel time is dependent on the load, direction of the current of the river, water depth, and the wind direction.

Currently, the ICTR model is limited by the calculation time. Future research on using a solution method which does not provide an optimal solution but an improvement to the current solution, could improve the possibility for extending the model. In the results of the ICTR model there is a significant optimality gap, therefore it is not certain what the optimal result is. It would be interesting to see what would happen if the gap decreases. This can be solved by increasing the running time or make the formulation of the problem more efficient, furthermore solution methodologies are potential research directions.

The ICTR and the benchmark model are deterministic models with the assumption that everything will go as planned. In reality this will not be the case, there are delays in the handling times of the containers and there are traffic jams.

We observed a decrease in CO2 even though the current model has the aim to decrease the costs, the amount of CO_2 emission is not in the objective function. It would be interesting to see what would happen if a CO_2 tax would be included.

The implementation of such a model requires a single central operator for the optimal result, which has the intention to decrease the costs of the entire network instead of their own company. It would be interesting how the stakeholders in this network could cooperate to achieve the maximum benefit for the entire network.

The solution strategy for the ICTR model and benchmark model could help to extend the network, containers, trucks, and moves. Further research is required to find a solution strategy with the intention to finally update the route for all the vehicles to a real-time situation.

Bibliography

[1] Richa Agarwal and Özlem Ergun. Ship scheduling and network design for cargo routing in liner shipping. *Transportation Science*, 42(2):175–196, 2008. ISSN 15265447. doi: 10.1287/trsc.1070.0205.

[2] J. Andersen and M. Christiansen. Designing new European rail freight services, 2009.

[3] Jardar Andersen, Teodor Gabriel Crainic, and Marielle Christiansen. Service network design with management and coordination of multiple fleets. *European Journal of Operational Research*, 193(2):377–389, 2009. ISSN 03772217. doi: 10.1016/j.ejor.2007.10.057. URL `http://dx.doi.org/10.1016/j.ejor.2007.10.057`.

[4] D. Anghinolfi, M. Paolucci, S. Sacone, and S. Siri. Freight transportation in railway networks with automated terminals: A mathematical model and MIP heuristic approaches. *European Journal of Operational Research*, 214(3):588–594, 2011. ISSN 03772217. doi: 10.1016/j.ejor.2011.05.013. URL `http://dx.doi.org/10.1016/j.ejor.2011.05.013`.

[5] Burak Ayar and Hande Yaman. An intermodal multicommodity routing problem with scheduled services. pages 131–153, 2012. doi: 10.1007/s10589-011-9409-z.

[6] Denise Lindstrom Bandeira, João Luiz Becker, and Denis Borenstein. A DSS for integrated distribution of empty and full containers. *Decision Support Systems*, 47(4):383–397, 2009. ISSN 01679236. doi: 10.1016/j.dss.2009.04.003. URL `http://dx.doi.org/10.1016/j.dss.2009.04.003`.

[7] Behzad Behdani, Yun Fan, Bart Wiegmans, and Rob Zuidwijk. Multimodal schedule design for synchromodal freight transport systems. *European Journal of Transport and Infrastructure Research*, 16(3):424–444, 2016. ISSN 15677141. doi: 10.18757/ejtir.2016.16.3.3151.

[8] Bob Bixby. The Gurobi Optimizer.

[9] Stefan Bock. Real-time control of freight forwarder transportation networks by integrating multimodal transport chains. *European Journal of Operational Research*, 200(3):733–746, 2010. ISSN 03772217. doi: 10.1016/j.ejor.2009.01.046. URL `http://dx.doi.org/10.1016/j.ejor.2009.01.046`.

[10] An Caris, Cathy Macharis, and Gerrit K. Janssens. Corridor network design in hinterland transportation systems. *Flexible Services and Manufacturing Journal*, 24(3):294–319, 2012. ISSN 19366582. doi: 10.1007/s10696-011-9106-3.

[11] Teodor Gabriel Crainic and Kap Hwan Kim. Chapter 8 Intermodal Transportation. *Handbooks in Operations Research and Management Science*, 14(C):467–537, 2007. ISSN 09270507. doi: 10.1016/S0927-0507(06)14008-6.

[12] Massimo Di Francesco, Michela Lai, and Paola Zuddas. Maritime repositioning of empty containers under uncertain port disruptions. *Computers and Industrial Engineering*, 64(3):827–837, 2013. ISSN 03608352. doi: 10.1016/j.cie.2012.12.014. URL `http://dx.doi.org/10.1016/j.cie.2012.12.014`.

[13] Alan L. Erera, Juan C. Morales, and Martin Savelsbergh. Global intermodal tank container management for the chemical industry. *Transportation Research Part E: Logistics and Transportation Review*, 41(6 SPEC. ISS.):551–566, 2005. ISSN 13665545. doi: 10.1016/j.tre.2005.06.004.

[14] Eurostat. Freight transport statistics - modal split - Statistics Explained, 2018. URL `https://ec.europa.eu/eurostat/statistics-explained/index.php/Freight{_}transport{_}statistics{_}-{_}modal{_}split`.

[15] Shahin Gelareh and David Pisinger. Fleet deployment, network design and hub location of liner shipping companies. *Transportation Research Part E: Logistics and Transportation Review*, 47(6):947–964, 2011. ISSN 13665545. doi: 10.1016/j.tre.2011.03.002. URL `http://dx.doi.org/10.1016/j.tre.2011.03.002`.

[16] Asvin Goel. The value of in-transit visibility for supply chains with multiple modes of transport. *International Journal of Logistics Research and Applications*, 13(6):475–492, 2010. ISSN 1469848X. doi: 10.1080/13675567.2010.482522.

[17] Wenjing Guo, Bilge Atasoy, Wouter Beelaerts van Blokland, and Rudy R. Negenborn. Dynamic and Stochastic Shipment Matching Problem in Multimodal Transportation. *Transportation Research Record: Journal of the Transportation Research Board*, 2674(2):262–273, 2020. ISSN 0361-1981. doi: 10.1177/0361198120905592.

[18] Arild Hoff, Arnt Gunnar Lium, Arne Løkketangen, and Teodor Gabriel Crainic. A metaheuristic for stochastic service network design. *Journal of Heuristics*, 16(5):653–679, 2010. ISSN 13811231. doi: 10.1007/s10732-009-9112-8.

[19] Martijn R Van Der Horst and Peter W De Langen. Transport Chains : A Major Community. pages 57–83, 2015.

[20] Chaug Ing Hsu and Yu Ping Hsieh. Routing, ship size, and sailing frequency decision-making for a maritime hub-and-spoke container network. *Mathematical and Computer Modelling*, 45(7-8):899–916, 2007. ISSN 08957177. doi: 10.1016/j.mcm.2006.08.012.

[21] Rafay Ishfaq and Charles R. Sox. Design of intermodal logistics networks with hub delays. *European Journal of Operational Research*, 220(3):629–641, 2012. ISSN 03772217. doi: 10.1016/j.ejor.2012.03.010. URL `http://dx.doi.org/10.1016/j.ejor.2012.03.010`.

[22] Hwa Joong Kim and Young Tae Chang. Analysis of an intermodal transportation network in Korea from an environmental perspective. *Transportation Journal*, 53(1):79–106, 2014. ISSN 00411612. doi: 10.5325/transportationj.53.1.0079.

[23] Shao Wei Lam, Loo Hay Lee, and Loon Ching Tang. An approximate dynamic programming approach for the empty container allocation problem. *Transportation Research Part C: Emerging Technologies*, 15 (4):265–277, 2007. ISSN 0968090X. doi: 10.1016/j.trc.2007.04.005.

[24] Peter W De Langen. Port competition and selection in contestable hinterlands ; the case of Austria. *European Journal of Transport and Infrastructure Research*, 1(7):1–14, 2007. ISSN 1567-7133.

[25] Peter W De Langen and Athanasios A. Pallis. ANALYSIS OF THE BENEFITS OF INTRA-PORT COMPETITION. *International Journal of Production Economics*, 57(1):311–316, 2006. ISSN 09255273. URL `http://dx.doi.org/10.1016/j.ijpe.2012.11.013`.

[26] Rie B. Larsen, Bilge Atasoy, and Rudy R. Negenbom. Simultaneous planning of container and vehicle-routes using model predictive control. *2019 18th European Control Conference, ECC 2019*, pages 2177–2182, 2019. doi: 10.23919/ECC.2019.8795657.

[27] Chun-hsiung Liao, Po-hsing Tseng, and Chin-shan Lu. Comparing carbon dioxide emissions of trucking and intermodal container transport in Taiwan. *Transportation Research Part D*, 14(7):493–496, 2009. ISSN 1361-9209. doi: 10.1016/j.trd.2009.05.002. URL `http://dx.doi.org/10.1016/j.trd.2009.05.002`.

[28] Arnt Gunnar Lium, Teodor Gabriel Crainic, and Stein W. Wallace. A study of demand stochasticity in service network design. *Transportation Science*, 43(2):144–157, 2009. ISSN 15265447. doi: 10.1287/trsc.1090.0265.

[29] Johan Löfberg. YALMIP: A toolbox for modeling and optimization in MATLAB. *Proceedings of the IEEE International Symposium on Computer-Aided Control System Design*, (October 2004):284–289, 2004. doi: 10.1109/cacsd.2004.1393890.

[30] Michael Maloni, Eric C Jackson, and Eric C Jackson. North American Container Port Capacity : An Exploratory Analysis. 44(3):1–22, 2005.

[31] Qiang Meng and Shuaian Wang. Liner shipping service network design with empty container repositioning. *Transportation Research Part E: Logistics and Transportation Review*, 47(5):695–708, 2011. ISSN 13665545. doi: 10.1016/j.tre.2011.02.004. URL `http://dx.doi.org/10.1016/j.tre.2011.02.004`.

[32] Qiang Meng and Xinchang Wang. Intermodal hub-and-spoke network design: Incorporating multiple stakeholders and multi-type containers. *Transportation Research Part B: Methodological*, 45(4):724–742, 2011. ISSN 01912615. doi: 10.1016/j.trb.2010.11.002. URL `http://dx.doi.org/10.1016/j.trb.2010.11.002`.

[33] Qiang Meng, Tingsong Wang, and Shuaian Wang. Short-term liner ship fleet planning with container transshipment and uncertain container shipment demand. *European Journal of Operational Research*, 223(1):96–105, 2012. ISSN 03772217. doi: 10.1016/j.ejor.2012.06.025. URL `http://dx.doi.org/10.1016/j.ejor.2012.06.025`.

[34] Martijn R.K. Mes and Maria Eugenia Iacob. *Synchromodal Transport Planning at a Logistics Service Provider*, pages 23–36. Lecture notes in logistics. Springer, 2016. ISBN 978-3-319-22287-5. doi: 10.1007/978-3-319-22288-2_2.

[35] Luigi Moccia, Jean François Cordeau, Gilbert Laporte, Stefan Ropke, and Maria Pia Valentini. Modeling and solving a multimodal transportation problem with flexible-time and scheduled services. *Networks*, 57(1):53–68, 2011. ISSN 00283045. doi: 10.1002/net.20383.

[36] Theo Notteboom and Jean Paul Rodrigue. The future of containerization: Perspectives from maritime and inland freight distribution. *GeoJournal*, 74(1):7–22, 2009. ISSN 03432521. doi: 10.1007/s10708-008-9211-3.

[37] Jennifer A. Pazour, Russell D. Meller, and Letitia M. Pohl. A model to design a national high-speed rail network for freight distribution. *Transportation Research Part A: Policy and Practice*, 44(3):119–135, 2010. ISSN 09658564. doi: 10.1016/j.tra.2009.11.006. URL `http://dx.doi.org/10.1016/j.tra.2009.11.006`.

[38] Michael Berliner Pedersen, Teodor Gabriel Crainic, and Oli B.G. Madsen. Models and tabu search metaheuristics for service network design with asset-balance requirements. *Transportation Science*, 43(2):158–177, 2009. ISSN 15265447. doi: 10.1287/trsc.1080.0234.

[39] Port of Rotterdam. Port vision 2030. *Port of Rotterdam 2030*, (December), 2011. URL `http://portofrotterdam2030.com/files/downloads/pdf/201106ID-FS024-E-RAMINGEN{_}2030.pdf`.

[40] Wenhua Qu, Jafar Rezaei, Yousef Maknoon, and Lóránt Tavasszy. Hinterland freight transportation replanning model under the framework of synchromodality. *Transportation Research Part E: Logistics and Transportation Review*, 131(March):308–328, 2019. ISSN 13665545. doi: 10.1016/j.tre.2019.09.014. URL `https://doi.org/10.1016/j.tre.2019.09.014`.

[41] Vasco Reis. Should we keep on renaming a +35-year-old baby? *Journal of Transport Geography*, 46:173–179, 2015. ISSN 09666923. doi: 10.1016/j.jtrangeo.2015.06.019.

[42] Violeta Roso. Evaluation of the dry port concept from an environmental perspective : A note. 12:523–527, 2007. doi: 10.1016/j.trd.2007.07.001.

[43] Koichi Shintani, Akio Imai, Etsuko Nishimura, and Stratos Papadimitriou. The container shipping network design problem with empty container repositioning. *Transportation Research Part E: Logistics and Transportation Review*, 43(1):39–59, 2007. ISSN 13665545. doi: 10.1016/j.tre.2005.05.003.

[44] Dong Ping Song and Jing Xin Dong. Cargo routing and empty container repositioning in multiple shipping service routes. *Transportation Research Part B: Methodological*, 46(10):1556–1575, 2012. ISSN 01912615. doi: 10.1016/j.trb.2012.08.003. URL `http://dx.doi.org/10.1016/j.trb.2012.08.003`.

[45] M. Steadieseifi, N. P. Dellaert, W. Nuijten, T. Van Woensel, and R. Raoufi. Multimodal freight transportation planning: A literature review. *European Journal of Operational Research*, 233(1):1–15, 2014. ISSN 03772217. doi: 10.1016/j.ejor.2013.06.055. URL `http://dx.doi.org/10.1016/j.ejor.2013.06.055`.

[46] Lóránt Tavasszy, Behzad Behdani, and Rob Konings. INTERMODALITY AND SYNCHROMODALITY. 2015.

[47] UN. Transports Combines, Terminology on Combined Transport, Kombinierten Verkehrs. *New York*, page 18, 2001.

[48] Bart van Riessen, Rudy R. Negenborn, and Rommert Dekker. Synchromodal Container Transportation: An Overview of Current Topics and Research Opportunities. *Computational Logistics, 6th ICCL '15*, 9335: 398–421, 2015. ISSN 16113349. doi: 10.1007/978-3-319-24264-4. URL http://link.springer.com/10.1007/978-3-319-24264-4.

[49] Manish Verma and Vedat Verter. A lead-time based approach for planning rail-truck intermodal transportation of dangerous goods. *European Journal of Operational Research*, 202(3):696–706, 2010. ISSN 03772217. doi: 10.1016/j.ejor.2009.06.005. URL http://dx.doi.org/10.1016/j.ejor.2009.06.005.

[50] Manish Verma, Vedat Verter, and Nicolas Zufferey. A bi-objective model for planning and managing rail-truck intermodal transportation of hazardous materials. *Transportation Research Part E: Logistics and Transportation Review*, 48(1):132–149, 2012. ISSN 13665545. doi: 10.1016/j.tre.2011.06.001. URL http://dx.doi.org/10.1016/j.tre.2011.06.001.

[51] Lu Zhen, Chengle Ma, Kai Wang, Liyang Xiao, and Wei Zhang. Multi-depot multi-trip vehicle routing problem with time windows and release dates. *Transportation Research Part E: Logistics and Transportation Review*, 135(January 2019):101866, 2020. ISSN 13665545. doi: 10.1016/j.tre.2020.101866. URL https://doi.org/10.1016/j.tre.2020.101866.

[52] Endong Zhu, Teodor Gabriel Crainic, and Michel Gendreau. Scheduled service network design for freight rail transportation. *Operations Research*, 62(2):383–400, 2014. ISSN 15265463. doi: 10.1287/opre.2013.1254.

A

Appendix Research Paper

Joint Optimization of Container and Truck Routes for a Synchromodal Network

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Abstract: When containers are transported on synchromodal bookings from their origin to their destination, the transport supplier can decide which combination of trucks, trains, and ships to use. This gives transport suppliers many options to route the container through the synchromodal network. Current literature on the individual routing of containers assumes that the trucks are always available and they do not consider empty truck kilometers. A model which individually routes both containers and trucks through a synchromodal network is presented in this paper. We study the effect of integrating the route of individual trucks and containers, considering costs, emissions, and empty truck kilometers by creating the *Integrated Container and Truck* (ICTR) model, and comparing it to the existing assumption in literature that trucks are always available when routing the container through a synchromodal network. Numerical experiments on a simulated, synchromodal, hinterland network are used to illustrate the model's potential.

1. INTRODUCTION

Global container transport has increased significantly in the last decades which results in an increase in container throughput (Notteboom and Rodrigue, 2009). Containers travel through the hinterland by truck, ship or train. In 2018, road transport was the leading mode of freight transport in the European union (52.4%) followed by maritime transport (30.0%) and rail transport (13.0%) (Eurostat, 2018). Truck transport is often the least environmentally friendly and the most expensive option. It is thus important that container routes do not enforce bad truck routes (Larsen et al., 2019).

The aim of this research is to investigate the impact of combining truck and container routing through a synchromodal network. This is achieved by creating the Integrated Container and Truck (ICTR) model, which can route both containers and trucks through a synchromodal network in an optimal way, considering costs, distance, and emissions. The model simultaneously decides how the containers travel (by truck, or by a combination with ship and/or train) and the route of the trucks (when the trucks are full and when the trucks are empty). The ICTR model is compared to a two-stage planning, with the existing assumption in literature that trucks are always and infinitely available to transport containers. The two-stage planning, which first determines the route of container, with the existing assumption, followed by optimizing the available trucks to transport the containers.

In this paper, first the current available transport models are explored, and secondly, the Key Performance Indicators (KPI) are identified (Section 2). Thirdly, the ICTR model is defined, followed by a two-stage model which represent current practice (Section 3). Hereafter, the two models have been compared in several, simulation experiments and the results are discussed which evaluate the total costs, CO_2 emissions, modal split and the amount of empty truck kilometers (Section 4).

2. LITERATURE

Based on Steadieseifi et al. (2014) the container routing models can be divided into three different planning horizons: the strategic, which relates to the investment decisions on the infrastructures, the tactical, which deals with optimally utilizing the given infrastructure (this is not applicable in the individual routing of containers), by choosing the services and transportation modes (truck, train, or ship), and the operational, which contains specific routing and timing. Operational models are relatively calculation intensive models, which are often solved by approximative methods. The routing problem of this research can be seen as an operational routing problem, due to the detailed routing of the containers and trucks.

An overview of the relevant literature can be seen in Table 1. The table shows if the model is Tactical or Operational (T/O). What modes are used in the model, Truck (Tr) and Ship (Sh) or truck, ship, and train (All). If empty truck trips (ETT) are considered to some extend. If the trucks are routed individually (Individual Routing of Trucks (IRT)) and if the containers are routed individually (Individual Routing of Containers (IRC)). If the model inputs do not vary over time which is indicated as Static(S) or vary over time which is indicated as Dynamic (D). If the solution is Approximated (app) or Optimal (Opt). Finally, what kind of network is used, a network with two nodes with one single origin and destination (single OD) or using multiple nodes (multi).

Table 1. Overview of models

	T/O	Modes	ETT	IRT	ICR	S/D	App/Opt	Network
Guo (2020)	O	All	No	No	No	D	App	multi
Zhen (2020)	O	Truck	Yes	Yes	No	S	Opt	multi
Larsen (2019)	O	All	Yes	No	No	D	App	multi
Qu (2019)	O	All	No	No	No	D	App	multi
Behdani (2016)	O	All	No	No	No	S	Opt	single OD
Mes (2016)	O	All	No	No	No	D	App	multi
Ayar (2012)	T	Tr&Ba	No	No	Yes	S	Opt	multi
This research	O	All	Yes	Yes	Yes	S	Opt	multi

Table 2. Different VRP problems

	Time windows	Depot	Multiple trips	Release date	Goods through network	O&D	Different modes
VRP	N	Single	N	N	N	Same	N
VRPTW	Y	Single	N	N	N	Same	N
Multi-D VRPTW	Y	Multi	N	N	N	Same	N
Multi-D&T VRPTW	Y	Multi	Y	N	N	Same	N
Multi-D&T VRPTW-R	Y	Multi	Y	Y	N	Same	N
This research	Y	Multi	Y	Y	Y	All	Y

When considering the operational models using all modes of transport, the current synchromodal containers models assume that there are infinite trucks available at any time. Where in real life, trucks must depart and return to depots, drive to a pickup point and a delivery point, etc. Behdani et al. (2016) optimize the schedule of the scheduled services on a single origin and destination. Mes and Iacob (2016) optimize the distance of the truck with the aim to decrease CO_2 emissions. Qu et al. (2019) consider the unexpected uncertainties in the model which could deviate from the original plan. Guo et al. (2020) match transport services and shipment requests optimally using a dynamic and stochastic model. In contrast to the other models, Larsen et al. (2019) consider empty truck travels, and find out that it has a significant influence on the outcome of the optimal route. All the operational models above consider trucks as flow, in other words, the trucks are not routed individually.

The routing of individual trucks through a network can be seen as a Vehicle Routing Problem (VRP), an overview of vehicle routing problems can be seen in Table 2. The truck routing of the model proposed in this research is uses parts of Zhen et al. (2020), which investigates a multi-depot multi-trip vehicle routing problem with time windows and release dates, which is a practical problem in the last mile distribution operations.Zhen et al. (2020) considers a multi- trip, terminal and depot problem with Vehicle Routing Problem with Time Windows (VRPTW) and release dates (Multi-D&T VRPTW-R). By using this vehicle routing model, it is possible for trucks to visit roads and hubs multiple times and still be able to know the exact time of that truck at a location. This model does not consider containers but packages which have to be delivered to the depot, the packages do not have the option to go through the network (on different trucks or modes), and the trucks do not have the option to drive to a different final depot.

The tactical model by Ayar and Yaman (2012) route containers through a deterministic network using infinite truck capacity and finite ship capacity. It has inspired the formulation of mode choice decisions and time window constraints in the ICTR model.

There are numerous models available which consider transport optimization (1), there is no model available which can solve the individual routing of trucks and containers through a synchromodal network.

The key performance indicators in synchromodal transport are costs, CO_2, time costs, and waiting time costs. Beside these KPIs, we evaluate ICTR on effective truck kilometers, which is the percentage of loaded traveled kilometers and can only be considered if individual truck routing is incorporated.

3. METHODOLOGY

The current models, which consider intermodal or synchromodal container transport assume that there are infinite trucks available at any time. Where in real life, trucks must depart and return to depots, drive to a pickup point and a delivery point, etc.

In order to address this research gap, we propose an Integrated Container and Truck Routing (ICTR) model. To evaluate this integrated model, we also developed a benchmark model which models the routing process in a two-stage fashion representing the current practice. Both are new models which are routing the trucks and the containers. The ICTR model integrates the route decision of the container and the truck and the benchmark uses the assumption of the current models.

3.1 Conceptual model

Both the ICTR and the benchmark model are static, deterministic models where the demand is known upfront and they are formulated as Mixed-Integer Linear Program (MILP). Figure 1 shows an overview of the model's inputs and outputs.

The network in the model is an arc and node network. The nodes are the hubs, where the containers can switch in mode and where containers and trucks are released and due. There are two different types of arcs, the road arcs, and the arcs for the scheduled services.

The input for the road network is the distance between the

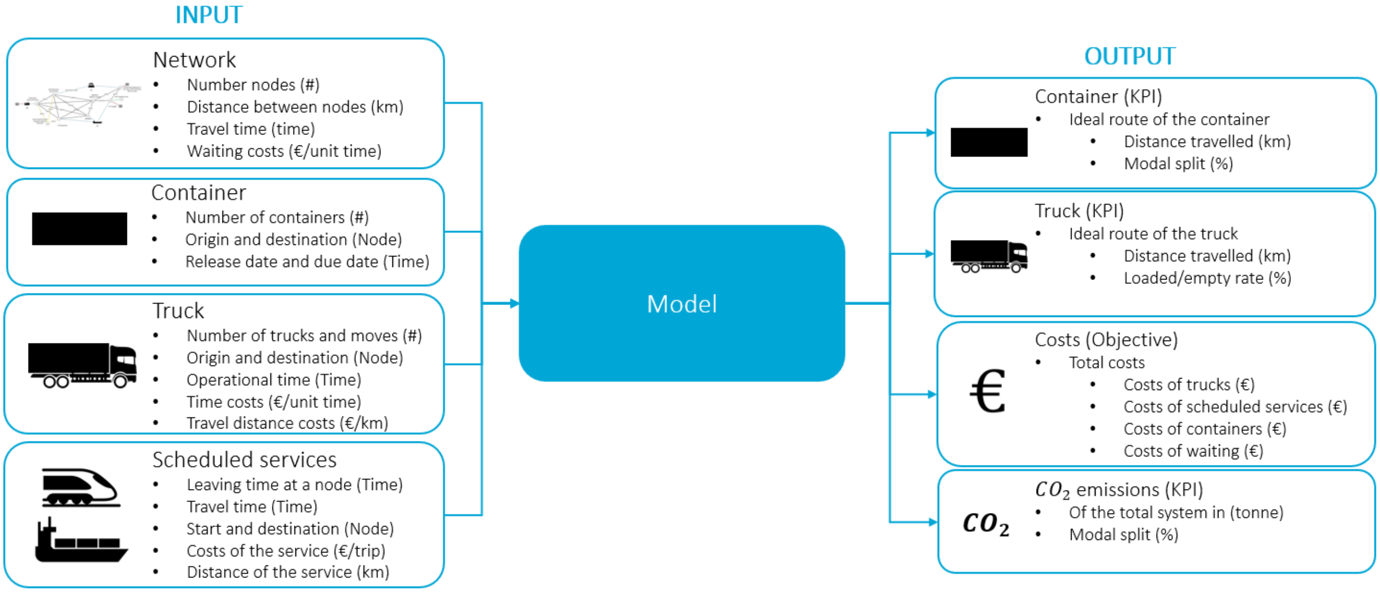

Fig. 1. Model overview

nodes. The road network can be used by containers and trucks. The input for the scheduled services is the details of the train and the ship: the departure time and the travel distance. Based on those inputs the travel distance and costs can be determined.

Containers in the model can use the scheduled services and the trucks to travel over the arcs. Each container is routed individually and requires an origin, destination, a release time, and a due date. The container can travel to all nodes but is not able to travel back over the same arc, so loops can be prevented. When the container arrives at a node, the time between the delivery and the pickup at the node is seen as waiting time.

Trucks in the model can drive through the system and can visit nodes multiple times. The trucks are modelled as a Multi-D&T VRPTW-R problem and is based on the model of Zhen et al. (2020).

A truck can travel between all nodes by roads. Trucks have an origin, a destination, a departure time and a due date, and a limited set of moves. A move is a travel over an arc and counted when the truck arrives at each node. The number of moves is introduced so the truck can be individually tracked and visit nodes multiple times. The time between the departure time and the due date is seen as the active time and can be used to drive through the system.

Both ICTR and the benchmark model only use the trucks needed, the trucks which do not have to transport a container stay at their origin. The trucks have an estimated velocity, cost per hour of usage and cost per kilometer of driving. There is no difference in empty driving and loaded driving when considering the costs.

The train and the ship in the model are assumed as scheduled services, with fixed departure times, transport times, and costs. Dependent on the kilometers of the service in combination with the mode (train or ship), the costs per kilometer and velocity are estimated. The trains and ship have limited capacity.

The objective of the models is to decrease the total costs of transport, including the costs for containers to be transported by modes, the waiting time of containers at nodes, and the time and distance of the trucks (loaded and empty). The truck costs includes the costs of the distance driven of the truck and the time costs from the moment it leaves the depot until it arrives at the depot. The costs of the scheduled services are divided in cost per mode and is per container using the service. The waiting time of the containers is the time that a container is waiting at a node which is not the first or last node.

Next to the cost outputs of the objective function, other outputs of the model are the KPIs which can be calculated based on the route choice of the model. For containers the total distance travelled and the modal split are evaluated. The modal split is how many percentages of kilometers a certain mode is used compared to the total container distance. For trucks the total distance travelled, including empty and loaded trips, and the ratio between the loaded and unloaded kilometers (effective ratio) are the KPIs.

Based on the driven distances and the amount of CO_2 emission emitted by the modes in tonne/TEU-km the amount of CO_2 emissions of the system can be determined. This is not part of the objective function, but will be used as a KPI to compare ICTR and the benchmark model.

Below are the sets and indices used in both models in Table 3.1.

Table 3. Notations used in this research

Notations	
Indices and sets	
T	set of trucks indexed by t
M	set of moves of a truck indexed by m
N	set of nodes in the network indexed by i and j
A	set of scheduled services indexed by a
K	set of containers indexed by k
Parameters	
(o_k, d_k)	the origin and final destination of container k
(o_t, d_t)	the origin and final destination of truck t
(m_0, m_f)	move 0 and final move
(r_k, q_k)	the operational with the beginning and end of container k
(r_t, q_t)	the start time and end time of the operational time of truck t
σ_{ij}	travel time by road from node i to node j (including loading and unloading)
l_a	departure time for scheduled service a
v_a	travel time for service a
(s_a, t_a)	starting point of service a and destination of service a
u_a	container capacity of a service
c_a	the costs of using service a
f_{ij}	the travel distance costs by truck from node i to node j
b_i	waiting costs of a container at node i
e^t	truck costs per unit time (driver costs)
Decision variables	
z_a^k	binary, 1 if container k is using service a, zero otherwise
z_{ij}^k	binary, 1 if container travels from i to j by a truck over a road, zero otherwise
$x_{ij}^{t,m}$	binary, 1 if truck t is moving from i to j in move m, zero otherwise
$y_{ij}^{k,t,m}$	binary, 1 if truck t in move m is transporting container k, zero otherwise
ρ_i^k	the time that container k arrives at node i
ξ_i^k	the time that container k leaves node i
$\tau_i^{t,m}$	the time that truck t in move m arrives at node i
ϕ^t	the time that truck t leaves the origin
w_i^k	waiting time of container k at node i when the container is not at the origin or at the final destination
M	a sufficiently large positive number

3.2 ICTR Model

The ICTR model is the first model able to route the individual trucks and containers through a synchromodal network. By integrating, the empty truck distance and time is included in the optimization. Below is the model formulated.

Objective function

$$\begin{aligned}\min \textstyle\sum_{k\in K} (\sum_{a\in A} c_a\, z_a^k + \sum_{i\in N} w_i^k b_i) \\ +\textstyle\sum_{t\in T} \sum_{i\in N} ((\tau_i^{t,m_f} - \phi^t)e^t \\ +\textstyle\sum_{m\in M} \sum_{j\in N} x_{ij}^{t,m} f_{ij})\end{aligned} \tag{1}$$

Routing of containers

$$\sum_{i\in N} z_{o_k,i}^k + \sum_{a\in A:s_a=o_k} z_a^k = 1 \quad \forall\, k\in K \tag{2}$$

$$\sum_{i\in N} z_{i,d_k}^k + \sum_{a\in A:t_a=d_k} z_a^k = 1 \quad \forall\, k\in K \tag{3}$$

$$\begin{aligned}\textstyle\sum_{j\in N} z_{ji}^k + \sum_{a\in A:t_a=i} z_a^k = \sum_{j\in N} z_{ij}^k \\ +\textstyle\sum_{a\in A:s_a=i} z_a^k \quad \forall\, k\in K,\ i\in N\setminus\{o_k, d_k\}\end{aligned} \tag{4}$$

$$\sum_{a\in A:t_a=i} z_a^k + \sum_{j\in N} z_{ji}^k \le 1 \quad \forall k\in K, i\in N \tag{5}$$

$$\begin{aligned}z_{ij}^k + z_{ji}^k + \textstyle\sum_{a\in A:(t_a=i\ \&\ s_a=j)} z_a^k \\ +\textstyle\sum_{a\in A:(t_a=j\ \&\ s_a=i)} z_a^k \le 1\ \forall\, k\in K, i\in N, j\in N\end{aligned} \tag{6}$$

Routing of trucks

$$\sum_{i\in N} x_{o_t,i}^{t,m_0} = \sum_{i\in N} x_{i,d_k}^{t,m_f} \le 1 \quad \forall\, t\in T \tag{7}$$

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

$$\begin{aligned}x_{i,i}^{t,m} + \textstyle\sum_{j\in N\setminus i} x_{ji}^{t,m} = x_{i,i}^{t,m+1} \\ +\textstyle\sum_{j\in N\setminus i} x_{ij}^{t,m+1} \quad \forall\, t\in T, m\in M\setminus m_f, i\in N\end{aligned} \tag{9}$$

Scheduled services

$$\sum_{k\in K} z_a^k \le u_a \quad \forall\, a\in A \tag{10}$$

Combining truck and container

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

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

Time of trucks

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

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

$$\tau_{d_t}^{t,m_f} \le q_t \quad \forall\, t\in T \tag{15}$$

$$\phi^t \ge r_t \quad \forall\, t\in T \tag{16}$$

Arriving time of containers

$$\begin{aligned}\rho_i^k \ge \tau_i^{t,m} - M(1 - y_{ji}^{k,t,m}) \\ \forall k\in K, t\in T, m\in M, i\in N, j\in N\end{aligned} \tag{17}$$

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

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

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

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

Departure times of containers

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

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

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

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

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

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

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

$$\rho_{d_k}^k \leq q_k \ \forall \ k \in K \tag{29}$$

$$\xi_{o_k}^k \geq r_k \ \forall \ k \in K \tag{30}$$

Binary variables

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

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

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

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

The objective function (1) minimizes the total costs of the model, considering the costs of using a scheduled service and the waiting costs for all containers and the costs of truck distance and time. Constraints (2)-(6) ensure that a container flows through a network from their origin to their destination, and are not able to make loops. Constraints (7)-(9) route the trucks through the network, if it is transporting a container in one of the moves, and when the truck leaves the origin the truck must travel to the final destination. Constraint (10) ensures the limitations of the capacity of scheduled services. Constraints (11) and (12) ensure the combination of a specific container to a specific truck in the case that the container uses a trip by road. Constraints (13)-(16) guarantee the truck arrival time at all nodes it visits. Constraints (17)-(21) ensure that the arriving time of the container at a node matches the used mode. Constraint (22)-(30) ensure the departure time of containers at nodes and the waiting time at nodes. Constraint (31)-(34) define the domain of decision variables. The big M, is used in several constraints, to linearize the constraints.

3.3 Benchmark Model

The benchmark model represents the current practice in the synchromodal transport models, which consider that for road transport of containers the trucks are always and infinitely available. The benchmark has two stages. In the first stage it analyses the optimal route of the container, considering that the trucks are always instantly available. This route is the input for the second stage of the benchmark, which determines the optimal route for the trucks to meet the demands of the route of the containers. This means that the optimization of the truck is not integrated as in the ICTR model.

The constraints used in the two stages are the constraints used in ICTR divided as indicated in Table 4. In the first stage, the objective function does not consider the entire route of the truck and the time the truck is used, only the distance costs when the truck is loaded. The first stage thus optimizes the objective function:

$$\min \textstyle\sum_{k \in K} (\sum_{a \in A} c_a \ z_a^k + \sum_{i \in N} w_i^k b_i + \sum_{i \in N} \sum_{j \in N} z_{ij}^k f_{ij}) \tag{35}$$

In the first stage, an additional constraint is furthermore needed. Constraint (36) creates time for the usage of trucks by including the time to travel by road from node i to node j to the arriving time at j for all containers, at all departing and arriving nodes.

$$\rho_j^k \geq \sigma_{ij} + \xi_i^k - M(1 - z_{ij}^k) \quad \forall k \in K, i \in N, j \in N \tag{36}$$

The second stage of the model determines the route of the truck and the specific times of containers and trucks at all nodes, considering the route of the container of the first stage. The objective function is the same as for the ICTR model (1), so the output is comparable. The constraints of the second part of the benchmark are the same as the ICTR model except for the constraints to determine the route of the container and the capacity limitations of the scheduled services.

4. SIMULATION EXPERIMENTS

In this section the ICTR Model and the benchmark model are applied on several different scenarios to find what differences and limitations the integration of trucks and container routes has compared to the existing planning methods.

4.1 Implementation of the models

Matlab is chosen as the programming software with the extensions of Yalmip and with the solver of Gurobi. The benchmark has less options during the calculations, and the outcome of Stage 2 is a feasible solution for the ICTR model. The solution procedure is illustrated in Figure 2, on the left is the input of the system and on the right is the output of the system. The benchmark model is the part of

Table 4. Overview of the constraints applied in the benchmark (with the first stage and the second stage) and the ICTR model

Modules	**Stage 1**	**Stage 2**	**ICTR**
Objective	(35)	(1)	(1)
Constraints			
Container routing	(2)-(6)	-	(2)-(6)
Truck routing	-	(7)-(9)	(7)-(9)
Scheduled services	(10)	-	(10)
Combining container and truck	-	(11),(12)	(11),(12)
Time of trucks	-	(13)-(16)	(13)-(16)
Container times	(19),(20),(21), (25),(26),(27), (29),(30),**(36)**	(17)-(30)	(17)-(30)
Binary variables	(31),(32)	(31)-(34)	(31)-(34)

the model which is solved first. The input is sent to Stage 1 which determines the optimal route without considering the trucks. If the route is feasible in Stage 1, the route determined in Stage 1 of the benchmark is used as the input of Stage 2. If Stage 1 of the benchmark is infeasible, then Stage 2 and the ICTR model will be infeasible too. Reason for this is that Stage 1 of the benchmark considers that trucks are always available, so if Stage 1 is infeasible, there is no option to arrive within the time windows with unlimited truck capacity. This results in an infeasible ICTR model because even without capacity limits for trucks the model is infeasible. If Stage 2 is infeasible, then the benchmark is not used as a warm start and the input is directly implemented in the ICTR model because the ICTR model can still be feasible.

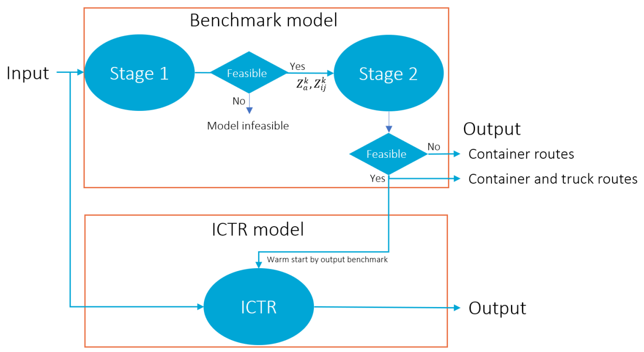

Fig. 2. Solution strategy

4.2 Scenarios

For evaluating the proposed ICTR, eight scenarios are designed by changing the input parameters such as the network (number of nodes), containers, trucks (and moves), and the scheduled services.

The network used in the base scenario includes seven nodes and several arcs, which can be seen in Figure 3. There are two scheduled services, one deep sea transport possibility and one train. The container terminals are at nodes 1, 3 ,5 and 7 and the truck depots are at node 6 and node 4. Node 7 is the moment that the container arrives in the Dutch waters and enters the network from the container ship. The depot at node 6 is place in the harbor of Rotterdam where trucks are parked. The depot at node 4 is at Apeldoorn, which is also the highway crossing.

The distances between the nodes are the real distances between the locations. For road transport they can be seen in Figure 3. The distances for the scheduled services are 220 km between RSC Rotterdam and Bad-Bentheim and estimated as 75 km from the sea/international terminal to the Maasvlakte in Rotterdam.

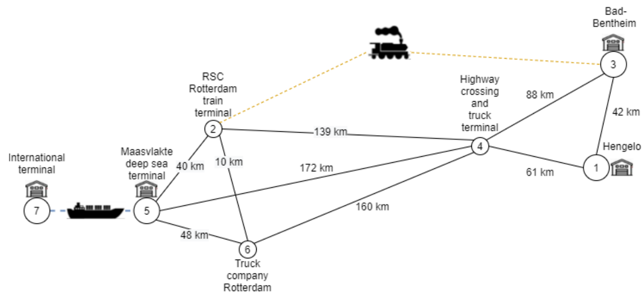

Fig. 3. Network

The Base scenario contains six containers, with a variety in the origins and destinations, with two different starting points and three different destinations. The inputs can be seen in Table 6.

There are two scheduled services, one from the international terminal to the Maasvlakte deep sea terminal and one from the train terminal in Rotterdam to Bad-Bentheim. The train is driving in both directions, twice a day. The ship is travelling once a day. These characteristics can be found in Table 5.

The costs and velocity of the modes are given in Table 7. The costs are based on Qu et al. (2019) and the CO_2 emission in ton/TEU-km are based on Kim and Chang (2014). The costs of waiting is chosen at €0.0005 euro per container per minute at every node and the truck time costs are €0.05 per minute.

Table 5. Scheduled services

Mode	Dep. node	Ari. node	Dep. time	Travel time	Capacity	Costs
Train	2	3	165	180	50	45
	3	2	525	180	50	45
	2	3	885	180	50	45
	3	2	1245	180	50	45
	2	3	1605	180	50	45
	3	2	1965	180	50	45
	2	3	2325	180	50	45
	3	2	2685	180	50	45
Ship	7	5	10	300	200	4,3
	5	7	600	300	200	4,3
	7	5	1450	300	200	4,3
	5	7	2040	300	200	4,3

Next to the base scenario there are seven other scenarios, the details can be found in Appendix A. The first scenario is the base scenario. Other scenarios focus on how the results change when considering a single truck, what influence import and export of containers has on the result, what happens when there are increased number of

Table 6. Input values of the scenarios

	Network	Container				Truck					Scheduled
		#K	Origin	Destination	Dep. and Due date	#T	#M	Origin	Destination	Dep. and due date	
Base	Base	6	[7 7 7 7 3 3]	[3 3 1 1 1 7]	[1,2000]	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	Tab. 5
Single truck	Base	6	[7 7 7 7 3 3]	[3 3 1 1 1 7]	[1,2000]	**1**	**20**	**[4]**	**[4]**	[1,2000]	Tab. 5
Import only	Base	6	[**7 7 7 7 7 7**]	[**1 1 1 1 1 1**]	[1,2000]	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	Tab. 5
Import and export	Base	6	[**7 7 7 1 1 1**]	[**1 1 1 7 7 7**]	[1,2000]	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	Tab. 5
Incr. containers and trucks	Base	**10**	[7 7 7 7 3 3 **7 1 3 3**]	[3 3 1 1 1 7 **1 7 7 7**]	[1,2000]	**6**	6	[4 4 **4** 6 6 6]	[4 4 **4** 6 6 6]	[1,2000]	Tab. 5
Tight time windows	Base	6	[7 7 7 7 3 3]	[3 3 1 1 1 7]	**Tab. A.1**	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	Tab. 5
Doubl. scheduled services	Base	6	[7 7 7 7 3 3]	[3 3 1 1 1 7]	[1,2000]	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	**Tab. A.2**
Extended network	**Fig. A.1**	6	[7 7 7 7 3 3]	[3 3 1 1 1 7]	[1,2000]	5	6	[4 4 6 6 6]	[4 4 6 6 6]	[1,2000]	**Tab. A.4**

Table 7. Cost input of the model

Mode	Capacity	Variable cost €*TEU/hr	Velocity km/hr	costs €*tue/km	$CO2$ ton/tue-km
Ship	120	0,86	15	0,057	0,0016
Rail	60	15	73	0.205	0,0007
Truck	1	31	90	0,344	0,0019

trucks, containers and moves, what happens when the time windows are tightened for containers, what happens when the scheduled services are doubled and what choices the model makes when the network has increased in size.

4.3 Results

For the base scenario, there is a significant improvement by using the ICTR over the benchmark model: 17% reduction in costs, 4% reduction in container distance, 7% decrease in total truck distance, and 2% decrease in emissions. The differences in cost in the base scenario between the ICTR and benchmark model are explained by the different route choices. Table 9 shows the route of all containers through the network, with the number of the specific container and the moves of that container. When the container has to travel from or to node 7 the only option is by ship, so the ship usage is the same for both models. The waiting time at nodes has doubled, this is explained by the difference in waiting cost for containers and the truck time cost (which is not included in the container routing of the benchmark model).

The benchmark model shows the expected result, which is that if the containers have the same starting point and destination, the route is the same because the availability of trucks is not considered when the route of the container is determined. This results in the same route for container 1 & 2 and container 3 & 4.

The ICTR model finds a better result by integrating the routing of the trucks and the containers. The difference in the routing can be seen in bold in the table. Container 3 takes the scheduled service from node 2 to 3 and truck from node 3 to 1, to use the truck more. When only considering the costs of loaded trucks, this would be less optimal (the transport by the truck is more expensive then using the train from node 2 to node 3), but when the cost of driving empty is considered, it is overall cheaper to use that capacity. Table 8 shows the differences between the benchmark and the ICTR model in costs, transport distance, total truck distance and the differences in total CO_2 emissions emitted. It can be seen in this overview, that in nearly all scenarios neither costs nor total container transportation distance increase, when the ICTR model is used. Although it is not considered explicit in the planning, integrated planning causes a slight decrease in the CO_2 emissions.

In the scenario with doubled scheduled services, the ICTR model has the most improvement compared to the benchmark model, an improvement of 25% in costs. The explanation for this is twofold. Firstly, the benchmark model costs increase due to the scheduled services chosen by the Stage 1 of the benchmark. When more departures are available, Stage 1 chooses services which depart close to the release time of the containers, but with just enough time to travel by truck. There is no time included for possible capacity issues of trucks. When doubling the scheduled services, this results in less time for potential truck capacity limitations to reach the departure time of the chosen scheduled service. If multiple containers are scheduled on the same service and there is less time to reach the departure time, this results in a peak demand for the trucks. The second part of the explanation is that the ICTR model has an improved result compared to the base scenario; it optimally uses the extra available scheduled services. The route of the containers and the trucks are the same for the ICTR model in the base scenario and the doubled scheduled services scenario, the difference is in the waiting time of trucks and containers. The model chooses a more optimal scheduled service which decreases the waiting time and the active time of the trucks.

The results of the scenarios show that a significant cost and CO_2 emission reduction is possible, in some scenarios 25% in costs and up to 11% of CO_2. Also, the amount

Table 8. Changes in KPIs when ICTR is used in percentage of the KPI obtained using the benchmark model

	Base	Single truck	Import only	Import and export	Increased containers and trucks	Tight time windows	Doubled scheduled services	Extended network
Decrease in costs	17%	16%	-	22%	15%	0%	25%	0%
Decrease in transport distance of containers	4%	4%	-	3%	2%	0%	4%	0%
Decrease in total truck distance	8%	7%	-	11%	7%	0%	-30%	0%
Decrease in CO_2 emissions	9%	9%	-	11%	7%	0%	-5%	0%

Table 9. Container routes in the Base scenario, the notation (1-2)T means that the container travels from node 1 to 2 by truck, if it is transported by schedules service, the indication is (1-2)S

Container	ICTR			
1	(7-5)S	(5-2)T	(2-3)S	
2	(7-5)S	(5-2)T	(2-3)S	
3	(7-5)S	**(5-4)T**	**(4-1)T**	
4	(7-5)S	(5-2)T	(2-3)S	(3-1)T
5	(3-1)T			
6	(3-4)T	(4-5)T	(5-7)S	
Container	**Bench**			
1	(7-5)S	(5-2)T	(2-3)S	
2	(7-5)S	(5-2)T	(2-3)S	
3	(7-5)S	(5-2)T	(2-3)S	(3-1)T
4	(7-5)S	(5-2)T	(2-3)S	(3-1)T
5	(3-1)T			
6	(3-4)T	(4-5)T	(5-7)S	

of effective kilometers of truck increase significantly, for instance in the base scenario where the effectiveness increases from 45% to 64%. The most important reason for possible benefits is the availability of trucks. When the trucks are not the bottleneck (and can be seen as always available) for the chosen route of stage 1 in the benchmark, then there is no benefit in using the ICTR model. But if there are limited trucks available, or there is cooperation required between trucks and containers to fulfill the demand the ICTR model has significant advantages. The benefits of using the ICTR model compared to the benchmark increase when there are more time restrictions. When trucks are not always available, or it has to be in time for the departure time of scheduled services the profits increase.

5. CONCLUSION

Integrating the route of containers and trucks in a synchromodal network improves the performance significantly. The current synchromodal models consider the modal choice for containers without the individual routing of trucks. When trucks are not infinite and at any time available at all node, there could be an entirely different situation. In reality trucks have a starting location, final location and time windows, this research shows the shortcomings of that assumption.

The benefits of the ICTR model compared to the existing models depend on the extend of capacity limitations of trucks. The limitations of the trucks are: moves, the time windows, origin and destination, and the number of trucks. If there are no capacity limitations due to trucks, the results of the models show no difference. If the number of moves are the bottleneck, the benchmark model can become infeasible or use ineffective roads, where the ICTR model could solve the scenario. If the time windows or origin and destination are the limitations, there is significant improvement if the depot is used as a place to change truck for a container. When the number of trucks are limited, the model is not able to transport multiple containers at the same time, in this case the ICTR model shows the best results.

In conclusion, combining the planning of containers and truck transport can decrease the cost up to 25%, increase in the effectiveness of trucks significantly and up to 11% in CO_2, but it is dependent on the location of the demand, the availability of trucks and the costs of all parameters. If there are limited trucks available with limited time, the possible benefits increase. Furthermore, there is CO_2 emission reduction without the focus on decreasing the emissions just by improving the efficiency of trucks.

There are several interesting future researches possible. First of all, the model can be made more realistic by considering the chosen parameters (e.g. handling times, cost parameters), the used network. Furthermore, the deterministic nature of the model is a limiting factor given the stochastic nature of such systems. Delays in the system and predictive information on travel times and demand can be incorporated for more advanced models. Moreover, the objective function can be enhanced to include CO2 emissions and potentially other KPIs. Furthermore, the computational time is a major challenge which limited our experimental work to small size instances. Therefore, studies on solution methods including heuristic algorithms are definitely a promising direction to pursue. Finally, the implementation of such a model requires a single central operator which has the intention to decrease the costs of the entire network instead of their own company. For a company with the availability of multiple terminals which is reachable by multiple modes the model is interesting. It would be interesting how the stakeholders in this network could cooperate to achieve the maximum benefit for the entire network.

REFERENCES

Ayar, B. and Yaman, H. (2012). An intermodal multicommodity routing problem with scheduled services. 131–153. doi:10.1007/s10589-011-9409-z.

Behdani, B., Fan, Y., Wiegmans, B., and Zuidwijk, R. (2016). Multimodal schedule design for synchromodal freight transport systems. *European Journal of Trans-*

port and Infrastructure Research, 16(3), 424–444. doi: 10.18757/ejtir.2016.16.3.3151.

Eurostat (2018). Freight transport statistics - modal split - Statistics Explained. URL `https://ec.europa.eu/eurostat/statistics-explained/index.php/Freight_transport_statistics_-_modal_split`.

Guo, W., Atasoy, B., Beelaerts van Blokland, W., and Negenborn, R.R. (2020). Dynamic and Stochastic Shipment Matching Problem in Multimodal Transportation. *Transportation Research Record: Journal of the Transportation Research Board*, 2674(2), 262–273. doi: 10.1177/0361198120905592.

Kim, H.J. and Chang, Y.T. (2014). Analysis of an intermodal transportation network in Korea from an environmental perspective. *Transportation Journal*, 53(1), 79–106. doi:10.5325/transportationj.53.1.0079.

Larsen, R.B., Atasoy, B., and Negenbom, R.R. (2019). Simultaneous planning of container and vehicle-routes using model predictive control. *2019 18th European Control Conference, ECC 2019*, 2177–2182. doi: 10.23919/ECC.2019.8795657.

Mes, M. and Iacob, M. (2016). *Synchromodal Transport Planning at a Logistics Service Provider*, 23–36. Lecture notes in logistics. Springer. doi:10.1007/978-3-319-22288-2_2.

Notteboom, T. and Rodrigue, J.P. (2009). The future of containerization: Perspectives from maritime and inland freight distribution. *GeoJournal*, 74(1), 7–22. doi: 10.1007/s10708-008-9211-3.

Qu, W., Rezaei, J., Maknoon, Y., and Tavasszy, L. (2019). Hinterland freight transportation replanning model under the framework of synchromodality. *Transportation Research Part E: Logistics and Transportation Review*, 131(March), 308–328. doi:10.1016/j.tre.2019.09.014.

Steadieseifi, M., Dellaert, N.P., Nuijten, W., Van Woensel, T., and Raoufi, R. (2014). Multimodal freight transportation planning: A literature review. *European Journal of Operational Research*, 233(1), 1–15. doi: 10.1016/j.ejor.2013.06.055.

Zhen, L., Ma, C., Wang, K., Xiao, L., and Zhang, W. (2020). Multi-depot multi-trip vehicle routing problem with time windows and release dates. *Transportation Research Part E: Logistics and Transportation Review*, 135(January 2019), 101866. doi:10.1016/j.tre.2020.101866.

Appendix A. EXPLANATION OTHER SCENARIOS

Single truck scenario The single truck scenario is a scenario which simulates the maximum shortage in trucks. This is the most extreme scenario for when there are limited transport resources available. Input values for the truck are that the single truck starts and finishes at node 4 and has 20 moves to move the containers as in the base scenario. Expected is that there will be significant differences between the benchmark (which assumes that trucks are always available) and the ICTR model, which includes the trucks in the routing process. The input values can be seen in Table 6.

Import only When there is one way transport of multiple containers, there can be a shortage of trucks at certain locations. In this scenario there are 6 containers travelling from node 7 to node 1 and only 5 trucks to transport them through the network. All the other input values are the same as in the benchmark, the input values can be seen in Table 6.

Import and export The import and export scenario places three containers at both sides of the network (1 and 7), and is completely the opposite to the import only scenario. Now the usage of trucks in a smart way can give benefits for the network. It is interesting to compare this results to the one way transport scenario, because the same amount of kilometers are travelled but this time the trucks can be more optimally used. Input values are except for the pickup and delivery node the same as the Base scenario and can be found in Table 6.

Increased containers and trucks The increased containers, trucks and moves scenario increases the throughput of the network, this results in more calculation time. The aim of this scenario is test the effectiveness off integrating trucks and container routing for increased throughput and what the limits of them model based on calculation time are.

The number of containers are increased to ten. There is one container travelling from node 7 to node 1 and one container from 1 to 7, this is through the network and requires at least two modes. There are two containers are travelling from node 3 to node 7 which improves the balance between the import and the export.

Tight time windows The tight time windows scenario is the scenario where the containers have tight time windows. Trucks in a normal network are assumed infinite and always available at every node. In real life this is hardly the scenario, this scenario shows that when integrating the truck in the routing of the container, a problem which is infeasible in the benchmark will be feasible in the ICTR model. The input values are the same as for the "Base" model but with the time windows shown in A.1.

Container 1,2,3 and 4 arrive in the network by the first ship from nodes 7 to 5 which means that they can not be earlier then t=310. The logical reachable train, if the train is used is train from node 2 to 3, the train departing at t=885 will be the one to take. To reach node 2, 4 loaded truck moves are required which can be done by 2 trucks. This means that container 1,2,3 and 4 can reach node 1

Table A.1. Input of container in the tight time window scenario

Container	Pickup node	Delivery node	Departure time	Due date
1	7	3	5	1070
2	7	3	5	1070
3	7	1	5	1000
4	7	1	5	1120
5	3	1	60	120
6	3	7	160	2000

within t=1070. From node 1, container 3 and 4 must be transported with 1 truck move for both to node 1.

Container 5, which is travelling from node 3 to 1, must be transported directly from the start and requires 1 loaded truck move. Container 6 is the most difficult one, this one has to reach node 5 before t=600 due to the schedule of the ship.

Doubled scheduled services The doubled scheduled services scenario doubles the number of scheduled services to find out what effect that has on the model. This means that for the containers in the situation to take a train or boat will have one sooner available which leads to decreased waiting times. The goal of this scenario is to find out what different choices both models make due to the tight schedules. Expected result: the benchmark model will route all containers through the same scheduled service (because there is no integration) and the integrated model will chose the optimal without.

In this scenario the input values are the same as for the Base scenario but with doubled scheduled services. The second train or ship departs around halfway of the first ship or train and has the same capacity and costs for containers. The new schedule is shown in Table A.2.

Table A.2. Doubled scheduled services

Mode	Departure node	Arriving node	Departure time	Travel time	Capacity	Costs
Train 1	2	3	165	180	50	45
	3	2	525	180	50	45
	2	3	885	180	50	45
	3	2	1245	180	50	45
	2	3	1605	180	50	45
	3	2	1965	180	50	45
	2	3	2325	180	50	45
	3	2	2685	180	50	45
Train 2	2	3	365	180	50	45
	3	2	725	180	50	45
	2	3	1085	180	50	45
	3	2	1445	180	50	45
	2	3	1805	180	50	45
	3	2	2165	180	50	45
	2	3	2525	180	50	45
Ship 1	7	5	10	300	200	4,3
	5	7	600	300	200	4,3
	7	5	1450	300	200	4,3
	5	7	2040	300	200	4,3
Ship 2	7	5	310	300	200	4,3
	5	7	900	300	200	4,3
	7	5	1750	300	200	4,3

Extended network The Base scenario determines the optimal route for containers and trucks in a network of 7 nodes. The question arises what would happen when the network size increases, with extra roads and extra scheduled services when considering the same input parameters for the containers and trucks as in the Base scenario. Due to the calculation time the network cannot be increased with a lot of nodes, so an increase of 2 nodes with roads and a shipping line are implemented in the model. With this result there can be estimated what a possible outcome could be when the network would increase even further. The estimated result is that due to the extra nodes, which lead to extra transport options, increase the number of possibilities for the routing of containers and trucks and will increase the benefits.

The extended network changes the Base network of 7 nodes to a network with 9 nodes, which can be seen in Figure A.1. Nodes 8 and 9 are added, which have connections to the road network and to an added shipline between node 8, stopping at Nijmegen and sailing towards Hengelo and returns the same way.

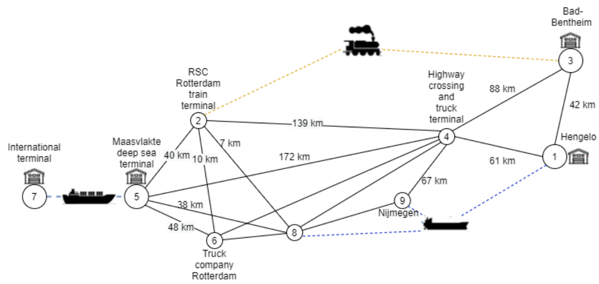

Fig. A.1. Extended network

Node 8 is a node in the center of the network and with connection to node 2,4,5,6 and 9. The network is connected between node 8 and 9 with a road and a scheduled service. Node 9 is a node located at Nijmegen and is connected to 4 and 8 by road and to 1 and 8 by ship.

The distances between the nodes are estimated based on real distance data. The distance can be seen in Table A.3.

Table A.3. Travel distance between nodes of the truck network in kilometers

		Arrivals								
		1	2	3	4	5	6	7	8	9
Departures	1	-	-	42	61	-	-	-	-	-
	2	-	-	-	139	40	10	-	7	-
	3	42	-	-	88	-	-	-	-	-
	4	61	139	88	-	172	160	-	144	67
	5	-	40	-	172	-	48	-	38	-
	6	-	10	-	160	48	-	-	16	-
	7	-	-	-	-	-	-	-	-	-
	8	-	7	-	144	38	16	-	-	112
	9	-	-	-	67	-	-	-	112	-

The scheduled services in the extended network are the same as in the Base scenario, with the extension of ships 2 and 3, who are sailing between node 8 - 9 - 1 and node 1 - 9 - 8 can be seen in Table A.4.

For the shipping line between node 8 - 9 - 1 and node 1 - 9 - 8, there are 2 ships sailing. One starting at node 1 with the departure time of 200, so containers appearing at an early time at node 1 or node 3 can use the ship. The ship is sailing in 480 time units toward node 9 where it stops and has time to load and unload any container, before the ship continuous toward node 8 in 440 time units. After node 8 the ship goes back in the same time as the other way towards node 9 and 1.

The other ship starts at node 8 at time 50, which means that only containers appearing early at node 5 can use this first services and is sailing with the same time units between the nodes from node 8 - 9 - 1 and afterwards back to node 1 - 9 - 8.

Table A.4. Scheduled services extended network

Mode	Departure node	Arriving node	Departure time	Travel time	Capacity	Costs
Train	2	3	165	180	50	45
	3	2	525	180	50	45
	2	3	885	180	50	45
	3	2	1245	180	50	45
	2	3	1605	180	50	45
	3	2	1965	180	50	45
	2	3	2325	180	50	45
	3	2	2685	180	50	45
Ship	7	5	10	300	200	4,3
	5	7	600	300	200	4,3
	7	5	1450	300	200	4,3
	5	7	2040	300	200	4,3
Ship 2	8	9	50	440	100	6,31
	9	1	550	480	100	6,88
	1	9	1100	480	100	6,88
	9	8	1600	440	100	6,31
Ship 3	1	9	200	480	100	6,88
	9	8	750	440	100	6,31
	8	9	1300	440	100	6,31
	9	1	1800	480	100	6,88

Appendix B. OUTPUT TABLES

Table B.1. Results of the scenarios (1)

Scenario		Base		Single truck		Import		Import and export		Incr. containers&trucks	
Model		Benchmark	ICTR	Benchmark	ICTR	Benchmark	ICTR	Benchmark	ICTR	Benchmark	ICTR
Costs (€)	Truck (empty and loaded)	562,2	474,6	485,1	419,2	Infeasible	777	932,5	732,9	1.232,0	1.056,0
	Ship	21,5	21,5	21,5	21,5	-	25,8	25,8	25,8	38,7	38,7
	Train	180	135	180	135	-	180	135	90	263,7	218,7
	Waiting costs	1	1,9	1,1	1,8	-	1,2	1	2,3	1,5	3,1
	Total	764,7	633,0(-17%)	687,7	577,5(-16%)	-	984,0	1.094,3	851,0(-22%)	1499	1276(-%15)
Container distance (km)	Truck	546	697	546	697	492	794	945	1096	1381	1531
	Ship	375	375	375	375	450	450	450	450	675	675
	Train	880	660	880	660	1320	880	660	440	1100	880
	Total	1801	1732(-4%)	1801	1732(-4%)	2262	2124	2055	1986(-3%)	3156	3086(-2%)
Modal split (%)	Truck	30%	40%	30%	40%	22%	37%	46%	55%	44%	50%
	Ship	21%	22%	21%	22%	20%	21%	22%	23%	21%	22%
	Train	49%	38%	49%	38%	58%	41%	32%	22%	35%	29%
Truck distance (km)	Loaded	546	697	546	697	-	794	945	1096	1381	1531
	Empty	629	389	580	353	-	848	1022	657	1381	1048
	Total	1175	1086(-8%)	1126	1050(-7%)	-	1642	1967	1753 (-11%)	2762	2579(-7%)
	Effective	46%	64%	48%	66%	-	48%	48%	63%	50%	59%
Processing (s)	Processing time	310	7200	52	7200	76	7200	601	7200	1080	7200
	optimality gap	0%	9%	0%	2%	Infeasible	12%	0%	39%	0%	38%
CO_2 emissions (ton)	total CO_2 ton of container travel)	3,45	3,13(-9%)	3,36	3,06(-9%)	-	4,46	4,92	4,36(-11%)	7,10	6,60(-7%)
	Truck	65%	66%	64%	65%	-	70%	76%	76%	74%	74%
	Ship	17%	19%	18%	20%	-	16%	15%	17%	16%	17%
	Train	18%	15%	18%	15%	-	14%	9%	7%	9%	9%

Table B.2. Results of the scenarios (2)

Scenario		Base		Tight time windows		Doubled scheduled		Extended network	
Model		Benchmark	ICTR	Benchmark	ICTR	Benchmark	ICTR	Benchmark	ICTR
Costs (€)	Truck (empty and loaded)	562,2	474,6	482,9	482,9	570,4	457,5	487,7	487,7
	Ship	21,5	21,5	21,5	21,5	21,5	21,5	35,3	35,3
	Train	180	135	135	135	225	135	90	90
	Waiting costs	1	1,9	1	1	0,5	1,1	0,7	0,7
	Total	764,7	633,0(-17%)	640,4	640,4(-0%)	817,4	615,1(-25%)	613,7	613,7(-0%)
Container distance (km)	Truck	546	697	697	697	326	697	682	682
	Ship	375	375	375	375	375	375	525	525
	Train	880	660	660	660	1100	660	440	440
	Total	1801	1732(-4%)	1732	1732(-0%)	1801	1732(-4%)	1647	1647 (-0%)
Modal split (%)	Truck	30%	40%	40%	40%	18%	40%	41%	41%
	Ship	21%	22%	22%	22%	21%	22%	32%	32%
	Train	49%	38%	38%	38%	61%	38%	27%	27%
Truck distance (km)	Loaded	546	697	697	697	326	697	682	682
	Empty	629	389	389	389	496	371	471	471
	Total	1175	1086(-8%)	1086	1086(-0%)	822	1068(+30%)	1153	1153 (-0%)
	Effective	46%	64%	64%	64%	40%	65%	59%	59%
Processing (s)	Processing time	310	7200	53	7200	54	7200	185	7200
	optimality gap	0%	9%	0%	9%	0%	5%	0%	37%
CO_2 emissions (ton)	total CO_2 ton of container travel)	3,45	3,13(-9%)	3,13	3,13(-0%)	2,93	3,09(+5%)	3,35	3,35(-0%)
	Truck	65%	66%	66%	66%	53%	66%	65%	65%
	Ship	17%	19%	19%	19%	20%	19%	25%	25%
	Train	18%	15%	15%	15%	26%	15%	9%	9%