

# Synchromodal Freight Transport Model for Cooperative Transportation Planning

## Synchromodales Güterverkehrsmodell für eine kooperative Transportplanung

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## Abstract

The increasing freight transport demand, the infrastructural saturation of the transport system and its effects on the society and the climate change are relevant factors, signaling that the achievement of a more sustainable, environmentally friendly and efficient transport system in Europe must be addressed. The information revolution, driven by the development of advanced communication technologies, will strongly affect how transportation and logistics will be conducted in the future. The sharing of information in real-time enables the integration of transport stakeholders through the entire network and opens new business possibilities, like cross-company transport cooperation making a flexible switch between transport modes and operators possible.

This work presents an intermodal freight transport network model capable of planning and simulating synchronized transport services. This work contributes to the field of synchronomodal transport in two ways: It creates a complete model environment for calculating generated transport costs and environmental impact and it proposes and evaluates three different optimization approaches for an optimal routing and assignment of transport orders from local and global point of view.

The benefit of flexible and integrated transport services is demonstrated by evaluating various test cases to encourage logistic service providers to offer synchronomodal services and to take common tactical decisions regarding their planning of freight transport routes.

## Zusammenfassung

Der steigende Güterverkehrsbedarf, die infrastrukturelle Sättigung des Verkehrssystems und deren Auswirkungen auf die Gesellschaft und den Klimawandel sind relevante Faktoren, die signalisieren, dass die Verwirklichung eines nachhaltigeren, umweltfreundlicheren und effizienteren Verkehrssystems in Europa angegangen werden muss. Die zukünftige Abwicklung wird stark von der Informationsrevolution beeinflusst, die von der Entwicklung fortschrittlicher Kommunikationstechnologien angetrieben wird. Der Austausch von Informationen in Echtzeit ermöglicht die Integration aller relevanten Akteure im gesamte Logistiknetzwerk und eröffnet somit neue Geschäftsmöglichkeiten, wie etwa die unternehmensübergreifende Zusammenarbeit im Transportwesen, die einen flexiblen Wechsel zwischen verschiedenen Verkehrsmitteln und Verkehrsunternehmen ermöglicht.

Diese Arbeit stellt ein intermodales Güterverkehrsnetzmodell vor, das die Planung und Simulation von synchronisierten Transportdiensten ermöglicht. Diese Arbeit leistet auf zwei Arten einen Beitrag auf dem Gebiet des synchronmodalen Transports: Zum einen wird eine Modellumgebung zur Berechnung der generierten Transportkosten und der Umweltauswirkungen des Transports erstellt. Zum anderen werden drei verschiedene Optimierungsansätze für eine optimale Routenführung und Zuordnung von Transportaufträgen vorgeschlagen, die jeweils von einer lokalen und einer globalen Perspektive aus betrachtet werden.

Der Vorteil flexibler und integrierter Transportdienstleistungen werden durch die Evaluation verschiedener Testszenarios aufgezeigt, um die Logistikdienstleister zu ermutigen, synchronmodale Transportdienstleistungen anzubieten und gemeinsame taktische Entscheidungen hinsichtlich der Planung von Güterverkehrswegen zu treffen.

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# List of Abbreviations

<b>API</b>	<b>A</b> pplication <b>P</b> rogramming <b>I</b> nterface
<b>BI</b>	<b>B</b> usiness <b>I</b> ntelligence
<b>CVRP</b>	<b>C</b> apacitated <b>V</b> ehicle <b>R</b> outing <b>P</b> roblems
<b>CPS</b>	<b>C</b> yber <b>P</b> hysical <b>S</b> ystems
<b>DSR</b>	<b>D</b> esign <b>S</b> cience <b>R</b> esearch
<b>DSS</b>	<b>D</b> ecision <b>S</b> upport <b>S</b> ystem
<b>EA</b>	<b>E</b> volutionary <b>A</b> lgorithm
<b>EC</b>	<b>E</b> uropean <b>C</b> ommission
<b>ERP</b>	<b>E</b> nterprise <b>R</b> essource <b>P</b> lanning
<b>EU</b>	<b>E</b> uropean <b>U</b> ion
<b>FIFO</b>	<b>F</b> irst <b>I</b> n <b>F</b> irst <b>O</b> ut
<b>FTNM</b>	<b>F</b> reight <b>T</b> ransport <b>N</b> etwork <b>M</b> odel
<b>GA</b>	<b>G</b> enetic <b>A</b> lgorithm
<b>GDP</b>	<b>G</b> ross <b>D</b> omestic <b>P</b> roduct
<b>GWP</b>	<b>G</b> lobal <b>W</b> arming <b>P</b> otential
<b>IoT</b>	<b>I</b> nternet <b>o</b> f <b>T</b> hings
<b>ICT</b>	<b>I</b> nformations <b>C</b> ommunication <b>T</b> echnologies
<b>IFTM</b>	<b>I</b> ntermodal <b>F</b> reight <b>T</b> ransport <b>M</b> odel
<b>ITS</b>	<b>I</b> ntelligent <b>T</b> ransport <b>S</b> ystem
<b>KPI</b>	<b>K</b> ey <b>P</b> erformance <b>I</b> ndicator
<b>LCA</b>	<b>L</b> ife <b>C</b> ycle <b>A</b> ssesment
<b>LU</b>	<b>L</b> oading <b>U</b> nit
<b>LSP</b>	<b>L</b> ogistics <b>S</b> ervice <b>P</b> rovider
<b>MCDM</b>	<b>M</b> ulti- <b>C</b> riteria <b>D</b> ecision <b>M</b> aking
<b>MES</b>	<b>M</b> anufacturing <b>E</b> xecution <b>S</b> ystem
<b>MFA</b>	<b>M</b> aterial <b>F</b> low <b>A</b> nalysis
<b>MSB</b>	<b>M</b> ega <b>S</b> wap <b>B</b> ox
<b>NRW</b>	<b>N</b> orth <b>R</b> hine- <b>W</b> estphalia
<b>NSGA</b>	<b>N</b> on-dominated <b>S</b> orting <b>G</b> enetic <b>A</b> lgorithm
<b>PL</b>	<b>P</b> arty <b>L</b> ogistics
<b>RL</b>	<b>R</b> einforcement <b>L</b> earning

<b>RQ</b>	<b>R</b> esearch <b>Q</b> uestion
<b>SA</b>	<b>S</b> imulated <b>A</b> nneling
<b>SCM</b>	<b>S</b> upply <b>C</b> hain <b>M</b> anagement
<b>SND</b>	<b>S</b> ervice <b>N</b> etwork <b>D</b> esign
<b>SOOA</b>	<b>S</b> ingle <b>O</b> bjective <b>O</b> ptimization <b>A</b> lgorithm
<b>TMS</b>	<b>T</b> ransport <b>M</b> anagement <b>S</b> ystem
<b>TEU</b>	<b>T</b> wenty-foot <b>E</b> quivalent <b>U</b> nit
<b>TSP</b>	<b>T</b> ravelling <b>S</b> alesman <b>P</b> roblem
<b>UML</b>	<b>U</b> nified <b>M</b> odeling <b>L</b> anguage
<b>WMS</b>	<b>W</b> arehouse <b>M</b> anagement <b>S</b> ystem

# Chapter 1

## Introduction

Driving on ring roads around mayor cities during working hours is probably one of the last things people are willing to do voluntarily during their leisure time – but it is one of the main reasons for this work. Spending a couple of minutes on the ring road of the city of Antwerp, Cologne or Paris during rush hour for example, will clarify to everybody how overloaded the transport network currently is. With an ever-increasing transport demand it becomes clear, that only building new and bigger roads and highways will not solve the problem. The high traffic density leads to further problems than just losing time during the transport of goods: It leads to pollution and to the waste of already scarce resources [OEC17]. These trends are pushing current governments to promote the development of a more efficient, sustainable, environmentally friendly and resilient European transport system. Consequently, the European Commission has set the objective to reduce the greenhouse gas emission by 60% by 2050 and to diminish the dependency on oil [Eur11]. The straight forward approach of improving the energy efficiency of the different transport modes can only be a first, though important step.

The attention is further fueled by the possibilities offered through the fourth industrial revolution (Industry 4.0): New technological developments, like the Internet of Things (IoT) and Cyber Physical Systems (CPS), offer a wide spectrum of opportunities for improvement to the current freight transport system [VHBH17]. Driven by the improvement potential offered by Industry 4.0 in transport and logistics, the idea of synchronomodality was born as the next logical step after intermodal transport.

Synchronomodality is seen as one of the concepts supporting the goal set by the European Commission: "30% of road freight over 300 km [must be] shifted to other [more environmentally friendly] modes of transport such as rail or waterborne transport by 2030, and more than 50% by 2050" ([Eur11]: 2). Together with the increasing availability of information in real-time, as well as the ubiquitous presence of flexible and highly developed information and communication technologies, the idea of a synchronized multimodal transport network becomes clear. If different transport services are

synchronized in terms of sharing and exchanging information, the flexibility of changing cargo between them will increase. If the services are owned by different companies, new cooperation will arise, provided that information's transparency and availability is given, improving the usage of the entire network. This makes synchromodal transport services a good answer to the challenges posed to the current transport network [vND15].

## 1.1 Problem statement and relevance

If these new developments are driven by Industry 4.0, a survey on advanced data analytics in different industry sectors from 2015 shows how big the gap to other sectors has become. Only 2% of the enterprises in the logistic sector, who took part in the survey, said that they made use of advanced data-driven analytical techniques, opposed to 21% of manufacturers in the automobile industry [Sta16]. Recently, new developments like intelligent transport systems [Ric12], automated and intelligent warehouses or the possibilities of a digital supply chain management [Blu14] have already found their way into the logistics sector. Despite of these developments and the increasing availability of data for all relevant processes, participating players in the logistic sector often seem to focus on long established processes rather than on these new, cost-effective innovations. Currently, traditional LSPs have a profound knowledge of transport and logistic processes, but most of them are not taking advantages of data driven optimization potentials as well as not working on the corresponding business models [Fen17].

Various definitions can be found for the term Industry 4.0 in scientific literature. For this work, the definition given by [Pla18] will be used: Industry 4.0 is “[an] emergence of dynamic, real-time optimized and self-organized cross-company value networks through the networking of people, objects and systems”. Following this definition, stakeholders (people) like shippers, carriers, logistic service providers (LSPs) and customers aim to transport goods (objects) from an origin to a destination, using various vehicles and transshipment equipment (systems), thereby forming a transport network. To comply with the complete definition of Industry 4.0, the transport network must be dynamically connected, which is intrinsic to any complex transport network, real-time optimized and self-organized.

The transfer of Industry 4.0 and its underlying principles pose a big challenge to all players in the logistics sector, having the power of transforming traditional logistic

processes, services and businesses deeply [VHBH17] [JLD14]. Therefore, the objective of research should be to create suitable conditions for all transport and logistic stakeholders to integrate resources, processes, supply chain actors and customers through information and communication technologies (ICT) into one network [Spr16]. The integration would allow stakeholders to take faster and more autonomous actions throughout the whole supply chain, giving the possibility to decentralize the control of resources and to optimize the decision process from a multiple point-of-views.

The four trends in logistics presented in [Fen17] should be in focus of researchers to comply with the objective named previously:

1. The establishment of communication and networking standards along a digitized supply chain and across all stakeholders [Dol+14],
2. The creation of service oriented collaboration platforms supporting an integrated transport planning, execution and procurement [tHR14] [Aro16],
3. A higher transparency and availability of information [Lum15],
4. A blur of the boundaries between production and transport [Jes17].

In all of the above presented trends, stakeholders need to accept and promote stronger network cooperation and collaboration, in order to exploit the full potential of the digitization in the context of the fourth industrial revolution. Thus, this work will focus on the challenges and improvements linked to the idea of synchromodal transport or synchromodality. To put in a nutshell, synchromodal planning can be defined "as the combination of intermodal freight transport planning with real-time switching" ([ZP16b]: 3) between transport modes, transport operators and LSPs [van+13].

The optimization of logistics chains through a synchromodal transport network is still a young research area in transportation planning. According to [ali] and [alice], the following research fields and needs must be addressed in order to promote and enable synchromodal transport services within the European transport network:

- A dynamic planning and simulation of transport routes and transport patterns
- Evaluation of customer preferences, busy routes, bottle necks and available resources of hubs and transport modes.
- Simulations and forecast analysis in order to learn about repeated connections and to optimize transport performance
- Define common KPIs and design principles for EU freight transport
- Research gap in the development activities focusing on data analytic and demand predictive methods

This work will offer a collaborative synchromodal freight transport model to support LSPs in their tactical and operational decisions regarding the optimal planning of freight routes, cargo distribution and the selection, as well as design of the best set of transport services. Thus aiming to introduce the fourth industrial revolution a bit further to transport and logistics, closing the gap to other sectors like production, where it was originally developed.

## 1.2 Research Scope

To support the optimization of the logistic processes, an intermodal freight transport network with synchromodal services will be created in this work to facilitate synchromodal transport planning. The focus is set on the integration and cooperative planning of multimodal transport services, enabling a flexible and dynamic service network design. In the article of Crainic, the service network design (SND) is defined as "the set of main tactical issues and decisions relevant for this type of carriers [carriers and LSPs inside an intermodal network]: the selection and scheduling of the services to operate, the specification of the terminal operations, and the routing of freight" ([Cra00]: 2).

An analysis of the state of the art in the research fields of service network design (SND), synchromodal transport and finally, mathematical modeling approaches, establishes the basis for the characteristics and implementation requirements of the synchromodal model presented in this work. The creation of a detailed global freight transport network model (FTNM) enables the dynamic simulation of the current European transport network and its services, considering collaborative freight transport, while optimizing the cargo routing, its distribution and transport services' capacity. As a result, transport operators can use the model to decide on their planning of freight routes and their choice of intermodal services, while shippers receive an optimized intermodal transport route.

In order to offer guidance to the reader, the following research questions will be answered sequentially in the course of this work.

### **RQ 1 - Network modeling**

*How can a multimodal transport network be dynamically modeled in order to analyze container flows, transport services' capacities, transport schedules, monetary costs and environmental impact?*

To promote transport cooperation in order to increase the efficiency of resources' usage, there is a need to analyze the capacity of the current transport network, simulating cargo flows, intermodal transport services and their schedules. Without this analysis it will be impossible to implement a synchromodal network in highly congested regions. Therefore, this first research question focuses on the development of a simulation environment, which will enable the measurement of local and global transport costs, the environmental impact and the design of transport services, considering the freight transport is transacted in a multimodal transport network.

This first research question will present the modeling of a synchromodal transport network in detail, featuring two detailed models for measuring the monetary costs and the environmental impact of the network. Together, these models build a simulation environment, that is able to flexibly and dynamically calculate feasible transport routes for in-coming customers' orders, supporting main transport decisions like dispatching of orders, i.e. the assignment of transport services, as well as allowing the exploration of optimal services' schedules and their capacities.

### **RQ 2 - Transportation planning optimization**

*How will a collaborative optimization model, that supports an efficient assignment of in-coming customer's orders to the remaining free slots, look like for a more cost-effective and environmentally friendly transport?*

With the models in place, the actual optimization of the resources' utilization can be performed, in order to demonstrate the potential behind a synchromodal network. An optimization algorithm for the cargo assignment in a synchromodal network is developed, using current network data and the models created for modeling and evaluation of monetary and environmental transport impact in the first research question. This algorithm supports the dispatching process for in-coming orders (customers' shipments). As a result, the best intermodal routing for an order, the best cargo distribution and the optimal service's utilization for the IFTN are set.

Research question two will illuminate the optimization of cargo distribution from a local point of view. The transport routing is optimized at the time an order is assigned, aiming at minimum transport costs for an order.

### **RQ 3 - Global optimization**

*How can the transport network and its resources be more efficiently used from a global optimum point of view?*

This research question investigates the improvement of the optimization algorithm for order assignment and routing from a global optimum point of view. The use of genetic algorithms (GAs) for exploring the solution space in order to achieve a set of optimal solutions for a synchromodal transport distribution will be presented. Different approaches and settings of a single objective algorithm for order assignment will be analyzed. Thereby, new genetic operators are created for addressing the specific problem of order sequencing to support an optimal cargo distribution, while taking into account the given transport demand uncertainty.

The use of GA is further applied for solving multi-objective problems in transport networks. Minimizing both, the monetary transport cost and the environmental impact at the same time, is presented as an example. The outcome of this third research question are three different global optimization approaches based on GA, addressing the improvement of cargo distribution, transport service design and the routing of orders.

#### **RQ 4 - Transfer and further applications**

*Which research field can also profit from the developed optimization model for synchromodal transport?*

The presented model is developed for the European freight transport network, but its approach can be transfer to a lot of similar planning situations in different contexts, from urban logistics and Less-Than-Truckload (LTL) transportation to transport planning and cooperation between automated guided vehicles in production.

The transferability of the model will be discussed for the field of autonomous driving, more concrete for the transport planning challenges arising when implementing truck platooning. Actors involved in road freight transport will need to coordinate their shipments closely in order to selected optimal routes for the platoon. As data availability, integration and communication is growing rapidly with the first autonomous trucks on the road, the field of truck platooning represents the ideal context to implement the idea of synchromodal services. This future technology creates a new way of cooperative road transport and will pose new research questions to planners regarding fleet management and routing of trucks. The optimization approach presented in this work can help planners on routing and platooning settings decisions in road transport.

## 1.3 Structure and outline of the thesis

The structure of this thesis follows the methodology of the design science research (DSR), in which the different phases and knowledge flows are an iterative process of development and learning through the building of artifacts [VK15]. [Figure 1.1](#) presents the structure of this thesis based on the DSR methodology and outlines the relation between chapters and research questions.

Following this introduction, this dissertation contains seven additional chapters. The second chapter presents the state of the art and the characteristics of synchromodal transport. Based on well-known publications on freight transport network modeling, SND and synchromodal transport services representation, the third chapter discusses the requirements for the synchromodal transport model developed in this work. It gives an answer to the question of how a multimodal transport network can be modeled in order to reflect the underlying dynamics and to analyze container flows, transport costs and the resulting environmental impact. The fourth chapter presents a detailed description of the developed synchromodal model, including its architecture, modules, parameters and variables. The fifth chapter implements the model (constructing the artifact) and provides an answer to the question of how such a model allows a user to optimize container flows from a global point of view. Chapter six focus on the model's evaluation and application scenarios, presenting the optimization results for an exemplary multimodal network. The transferability of the research done in the context of this work will be presented and discussed in chapter seven. The chapter also contains some thoughts about possible improvements to the developed model, as well as a critical discussion of the next steps for the model's evaluation and application. Finally, chapter eight presents the conclusions and an outlook.

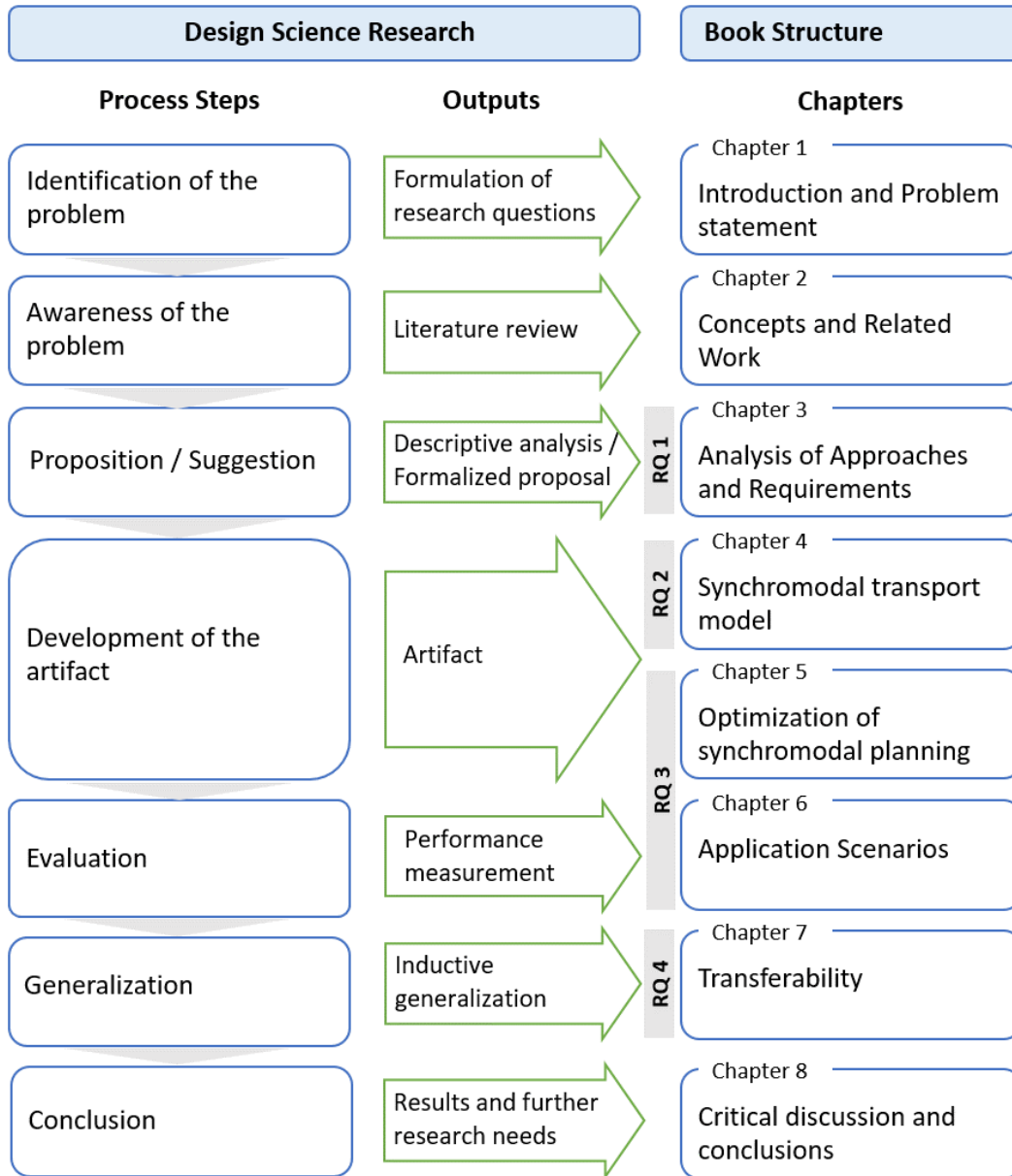


FIGURE 1.1: Structure of the thesis based on [VK15] and [DLA15]

## Chapter 2

# Fundamental concepts and delimitation of the research subject

The transport and logistic sector plays an important role in every country being a prerequisite for economic progress. In Europe the freight transport logistics sector contributes significantly to the economy with an estimated value of almost 14% to EU GDP [Pub15]. The set of services being responsible for the movement of cargo, planning and managing the transport and storage operations from cargo owner to receiver over the complete supply chain are the services defining the term of logistics [Wat03].

Logistic services are crucial for the free flow of goods in Europe. They contribute to employment and enable an efficient performance of other services and economic activities. Within the European Union, studies have estimated that the logistic sector represents a market volume of about 878 € bn in 2012 in the EU-27 and the largest logistic nation with about a quarter of the total volume is Germany [Eco+15]. These figures highlight the importance of the sector in Europe and of course the role of Germany as a transit country.

The performance of the logistic sector varies between European countries as a result of differences in economic and industrial strength, population density, geographical conditions and quality and quantity of infrastructure. The report presented by the European Commission in 2015 summarized three main problems of the sector [Eco+15]:

- rising costs, in particular for transport activities,
- increasing negative external effects like the environmental footprint linked to the energy consumption and
- insufficient suitable personnel.

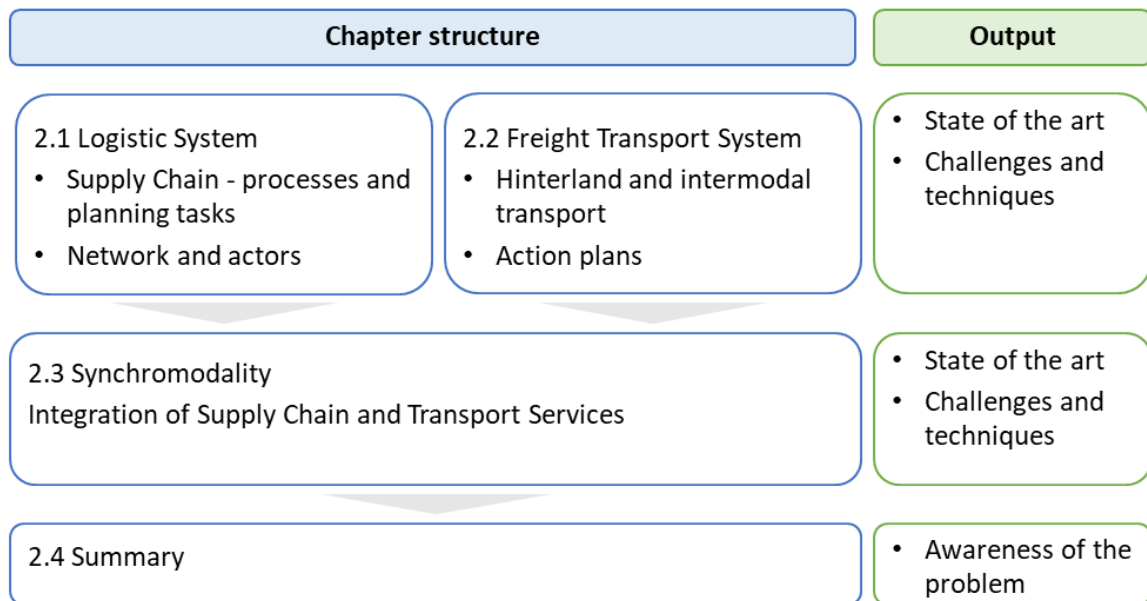


FIGURE 2.1: Chapter structure and content flow

Besides these problems, the sector is facing a large number of external developments: technology-driven trends like e-commerce or digital procurement and developments focusing on enhanced collaboration and integration within the logistical chain, e.g. enhancing collaboration in multi-modality [Eco+15]. These developments have the potential for increasing the efficiency of the logistics sector but of course the stakeholders involved in transport and logistic activities have to adapt and prepare to these changes.

In this chapter main transport and logistic concepts and the related work in the field of distribution logistics and specially in the field of synchromodality are presented. The awareness of the problem is described together with an overview of current and future developments in the logistics field, that have great potential for revolutionizing the way transportation and logistics are performed. Furthermore, an overview of the logistics processes, actors and services is given while current problems and challenges in European hinterland transport are discussed. [Figure 2.1](#) presents chapter's structure and content flow.

## 2.1 Logistic system

The concept of supply chain has been extended in the last years with the consideration of cross-company chains, the so called Supply Chain Management (SCM). The supply or logistic chain is the system, that encompasses the entire flow of goods from suppliers

to and within a company and from there to customers. This approach has increased the importance of cooperation between all stakeholders in order to integrate logistic processes. **Figure 2.2** presents three different main areas of a exemplary company logistic chain. The focus of each area is given in the list below:

- Procurement logistics focusing on the planning of material flow from providers to raw material's warehouses or directly to factory plants.
- Production logistics considers the material flow from raw material's warehouse to the storage of the final product. This term is also known as intralogistics, which makes reference to the material flow related to the production steps including connected storage and transport processes.
- Distribution logistics focus on the delivery of end products to the costumer.

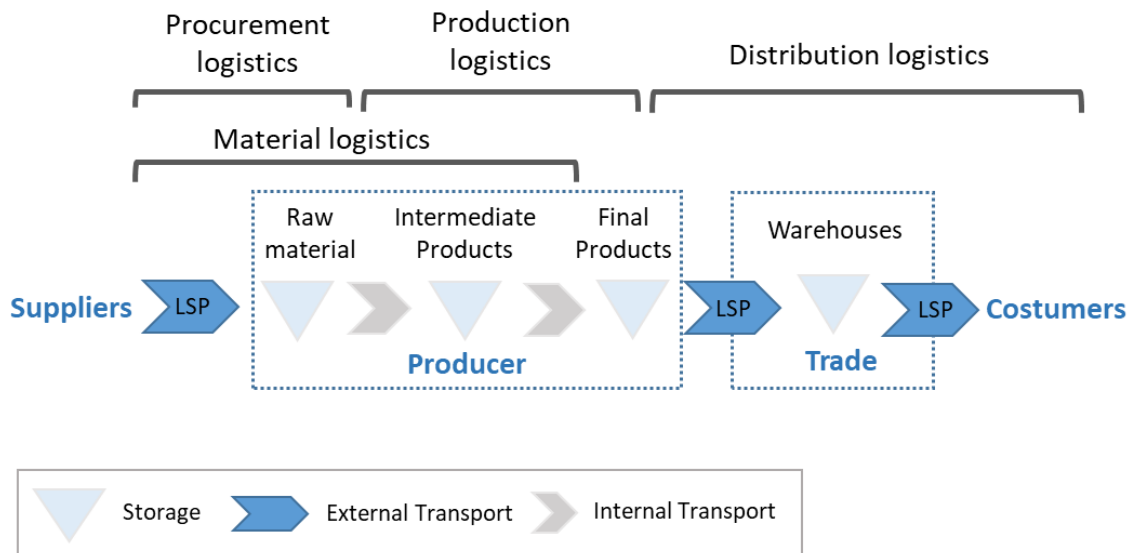


FIGURE 2.2: Supply Chain adapted from [Arn08] and [GF13]

Besides these three main material flow areas in a company supply chain, the term of disposal logistics is added, to denote the logistic processes in charge of handling waste material generated within production and logistic processes, preventing environmental pollution and the waste of resources. The logistic service provider, in most cases an external contracted company, is responsible for the external freight transport.

These logistic areas are useful to understand the different logistic processes inside the supply chain, but in fact the logistic system has to be considered in a holistic form, where all logistics processes are interconnected and integrated in a same layer. The globalization and the worldwide trade and commerce implies that the logistics has to integrate the various value chains into global operating networks. In consequence, one

of the main challenges for the further development of a sustainable transport network in Europe is the service integration between different stakeholders. For a successful integration, processes need to become more flexible in a fast changing environment like the European transport network.

### 2.1.1 Logistic processes and planning tasks

As mentioned above the supply chain consists of different logistic processes. These are commonly divided in transport, warehousing, handling, picking and packaging processes [Arn08]. In addition to these tasks, information and communication services are needed for planing and controlling all logistic processes of the supply chain. Current software systems implemented in a company, like Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), Warehouse Management System (WMS) or Transport Management System (TMS) ensure that company's data, including the data of logistic processes, is recorded and available for usage in operational, controlling, reporting or decision-making processes.

Within a company, logistic processes or tasks are also often differentiated according to the direction of goods being transported into inbound and outbound logistics. Inbound logistics addresses the transportation, storing and delivering of in-coming goods, whereas outbound logistics focus on the goods going out of the business location. From a company's point of view, it is essential to ensure the efficiency of the logistic network, distributing the goods in an optimal way, so that associated transportation and storage costs are minimized. The Logistic Service Provider (LSP) is therefore in charge to balance inbound and outbound logistics to efficiently transport the goods, avoiding empty trips and maximizing vehicle's capacity utilization.

Taking into accounts these tasks the logistic costs can be derived and split in six areas: Transportation costs for the transport of goods, handling costs including equipment, picking costs, packaging costs, storage costs and management and information technologies systems costs [Arn08]. Sometimes the costs for ICT are distributed over the remaining five areas, since these costs however become more and more important and affect all areas of a company, it is interesting to track them as a own unit.

The design and control of logistic processes are normally planning tasks. The usual definition of planning considers the identification and determination of future activities, which are relevant and necessary for company's objectives. These planning tasks require a high level of coordination and are often divided regarding their planning horizon in long, middle and short term. [Figure 2.3](#) presents a matrix dividing the logistic planning tasks regarding their time horizon and occurrence in the logistic chain.

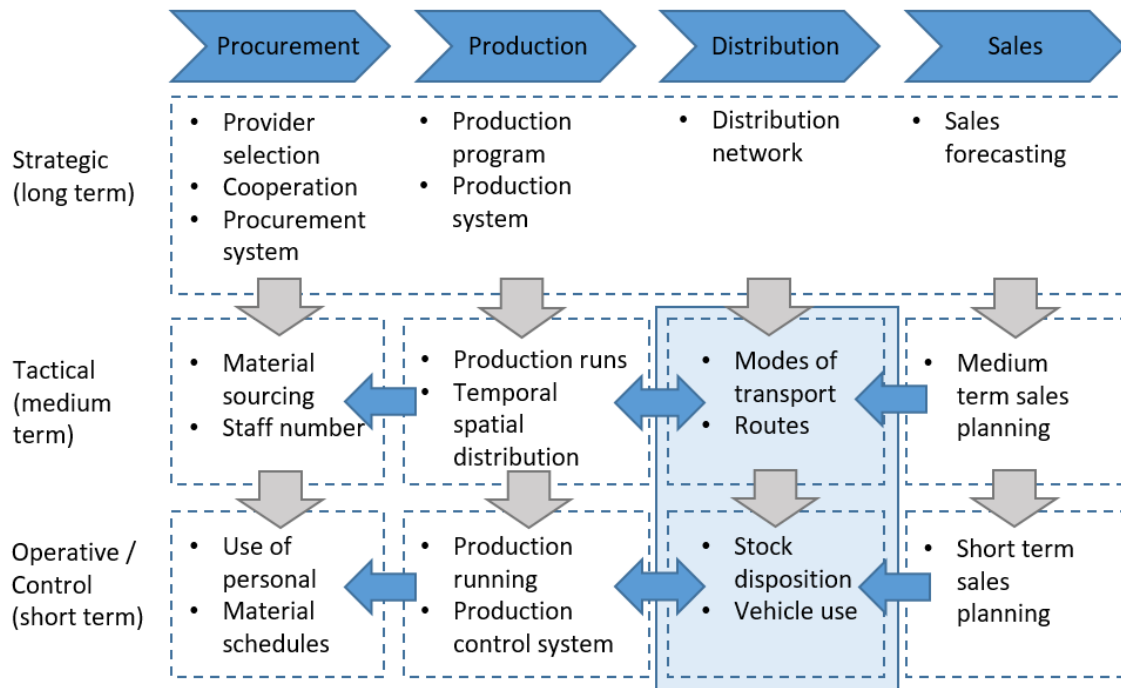


FIGURE 2.3: Logistic planning tasks adapted from [Arn08]

The strategic planning considers the activities affecting company's processes in a long term (several years) such as strategic partnerships, investment in new infrastructure or hub locations. The tactical planning integrates logistic decisions in a horizon of 6 to 18 months and strongly defining the transport framework and resources disposition. Finally the operative planning are all short term decisions related to the control of material flow normally inside a time horizon of 1 to 3 months.

The rectangle marked in blue in Figure 2.3 delimits the focus of this work to the tactical and operational level in the area of distribution. The traditional view and role of logistics is to serve and enable an efficient production, however this role is changing due to the highly important dependency between logistic and production processes and the improvement potential behind the 4.0 idea. Logistic processes are nowadays crucial when taking production related decisions.

### 2.1.2 Logistic network and actors

About 50% of manufacturing companies in Europe outsource their logistics to a Logistic Service Provider (LSP) [Eco+15]. This also means that the same number of companies manage their logistic services themselves. The aspect of cooperation between all involved supply chain actors at all levels is crucial for the global efficiency improvement of a logistic network. The promotion of vertical cooperation between

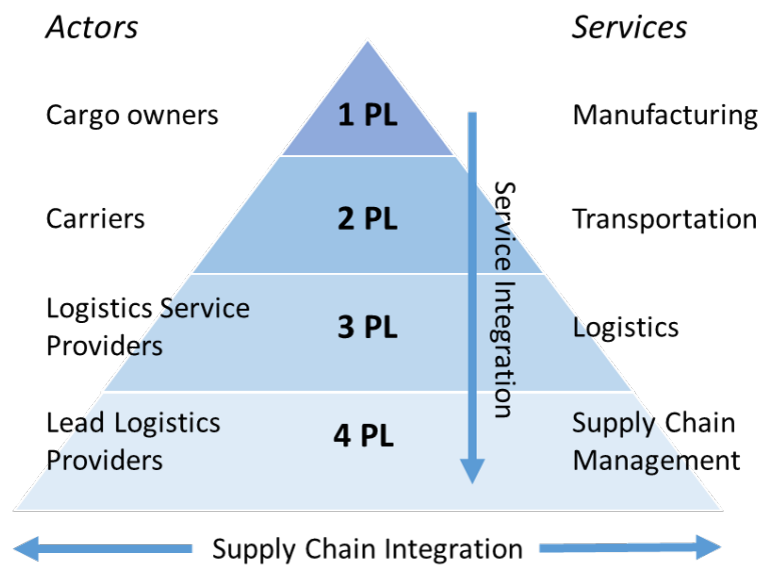


FIGURE 2.4: Actors, services and layers within the logistic supply chain based on [FRK11]

companies of the same sector, like collaboration between LSPs, as well as the promotion of horizontal cooperation, i.e. between companies from different levels of the supply chain, are two of the measures driven by the European Commission to strengthen the transport sector in Europe [Eur11].

Four categories of actors can be defined within the logistics supply chain with respect to their roles and their services offered. Their inter-dependencies are often represented in a pyramidal way [FRK11]. Figure 2.4 shows schematically the layers and relations between actors and services within the supply chain. Each layer represents the logistic parties involved in cargo transportation and integrates the service rendered of the above one. With a global overview of the supply chain, the involved actors, the schedules and capacities of network services and the used infrastructures, a fourth Party Logistics (4PL) builds and executes the supply chain solutions and pursues an improvement of resources utilization.

The line between the second and third layer is very thin as most of the LSP (3PL) are also carriers or transport operators. The second layer is very heterogeneous, ranging from road, rail and waterway transport operators to terminal operators and warehouse managers. Besides, at this level the number of actors involved increases rapidly when the transport of goods takes place within a multimodal network. The high level of competition, the different business focus and the variety and amount of actors involved increase the complexity of transport and logistic processes extremely. The top layer (1PL) represents the shippers, who own the cargo and are the customers of logistic services.

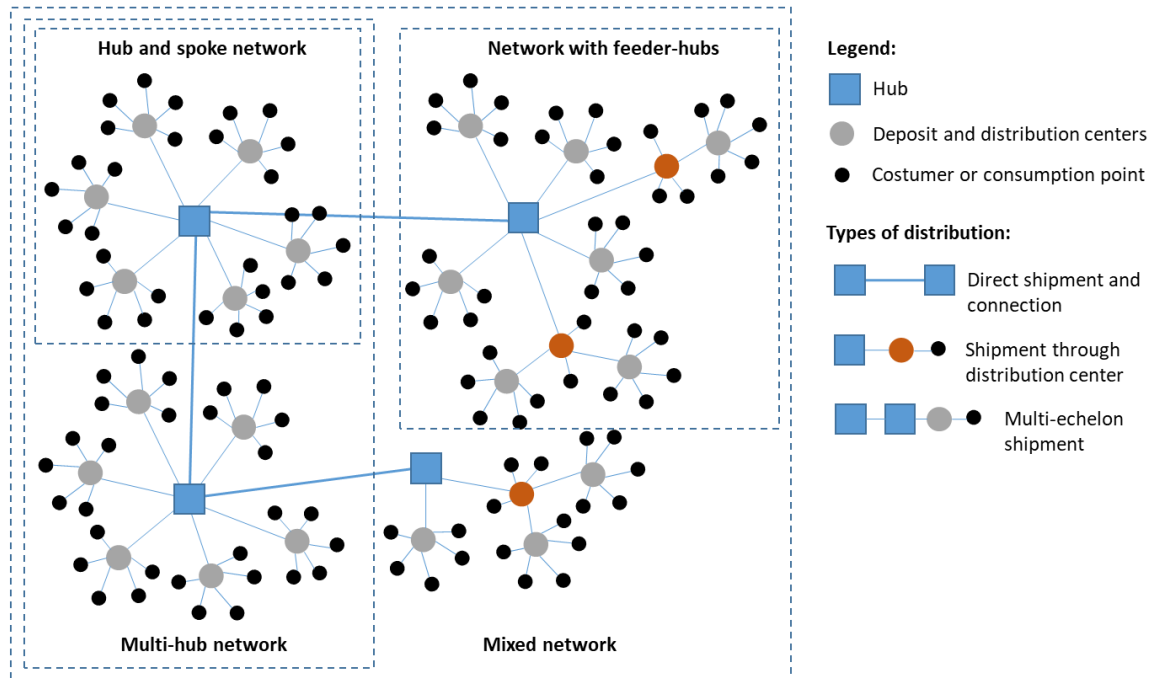


FIGURE 2.5: Network structure types adapted from [Arn08]

The transport logistic system is composed by a network of service providers and an infrastructural distribution network. Within the supply chain these actors deliver a service framed in an apparently simple common objective: transport customer's goods from their origin to their destination. In order to provide an optimal service all actors of the supply chain have to cooperate, exchange information and deliver a reliable service. Besides, logistic actors work in a common network, with the same policies framework and with the given transport infrastructure for each mode.

The strategical decision for freight forwarders and LSPs, where to locate their distribution centers, or for manufacturers, where to place their factories and warehouses, has currently a strong influence on the development of future transport and on the development of company's logistic chain. When, where and how to transport the goods are crucial questions, that are analyzed based on the possible transport connections and infrastructures. Unfortunately, this information is often not transparent or even unavailable. Current types of distribution networks in Europe can be classified as shown in picture [Figure 2.5](#). Each connection, from a simple, single connection to a complex network of connections through central hubs and distribution centers, should be integrated in a synchromodal network, where transport services are flexibly re-arranged. Thus, the transport network considered in this work is a mixed network with seamless connections between networks, representing the cooperation between all actors.

## 2.2 European freight transport system

The movement and demand in freight transport have increased very rapidly in the past two decades. Nowadays transport demand, world trade and GDP are strongly related. From 1988 to 2008 the world trade expanded rapidly and outpaced the GDP growth. In figures, the CPB World Trade index moved from 40 in 1988 to 120 in 2008 and to 140 in 2016 [Oe2]. The globalization, the relocation of production or the increase of the quality of life are some of the reasons explaining this enormous increase of transport demand. But further developments like an increasing e-commerce, the digitalization and faster ways to communicate, the automation of production, mobility and logistic processes together with environmental and social aspects are posing additional challenges to the European transport system. To overcome these challenges the European transport system is forced to continuously adapt and to develop new, more efficient ways of transportation.

Currently maritime freight transport is the main transport mode in long-distance trade and is responsible solely for 80% of the freight transport volume worldwide [Oe2]. For this reason main European seaports have experienced a considerable increase of their cargo movement within the last two decades. This aspect has generated high competitiveness between seaports in Europe, so that large investments in port infrastructure has been made. On the other hand this trend led to an overload of road transport infrastructure. Much of the infrastructure currently in use was calculated for a transport capacity much lower than today's traffic density, so that it has to be continuously renewed and repaired. Unfortunately, the geographical space in highly populated areas does not leave enough room for technical and infrastructural improvements to face the increasing transport demand.

Besides, the worldwide economy pushed the development of bigger transatlantic cargo ships, with the objective of a cheaper sea transport. The currently largest container ship in gross tonnage is able to transport more than 20.000 TEU [OOC18]. Main European seaport terminals are able to unload this ship in less than 24 hours, flooding the port's hinterland in a short period of time with a huge amount of freight. Therefore the infrastructure in the hinterland, i.e. the specific territory behind a port, which mainly serves as transit territory for the transport of goods, the port accessibility and connectivity are increasingly crucial factors for the success of the hinterland region and hence for Europe as a whole.

The European regions with stronger logistics hubs in Europe, also called the blue banana, is a high dense region with a high transport demand, stretching from United

Kingdom through Belgium, the Netherlands, western and southern Germany to Switzerland and northern Italy [Col13]. These regions are also strongly affected by the operation of some of the biggest ports worldwide, like Hamburg, Rotterdam, Antwerpen or Bremen [Wor]. Consequently, the hinterland area of these regions affected by the increasing transport has grown significantly in the last years.

Maritime transport is also the most important mode for long distance transport of goods from or to the EU. A total of 3.8 billion tonnes gross weight have been handled in 2015 in the EU [Sta]. Three ports located on the coast of the North Sea, Rotterdam, Antwerpen and Hamburg are the leaders in gross weight of goods handled and in terms of the volume of containers handled in the EU. The port of Rotterdam alone handles already 10% of the total tonnage [Sta]. These numbers explain the importance of an efficient transport logistic system in Europe in order to deliver the goods all over the European continent.

Ports across Europe are forced to keep up with the increasing transport demand by new expansion plans. The strong competition between the seaports can be recognized by the large investments in infrastructure of the main ports. For example the port of Rotterdam will increase the container handling throughput from 11.6 million TEU per year in 2013 to 30 million TEU per year in 2035 with the construction of Maasvlakte 2 [Por11] [Beh+14].

A similar situation in many European ports has drawn the attention to their hinterland and the resulting problems for the citizens. The area of influence of a port is not only defined by its near surroundings, but also by its ability for delivering freight in ever-shorter time to the hinterland. In order to guarantee a well-functioning transport and supply chain, ports' expansion plans to increase freight handling capacities have to be considered together with new transport concepts, policies, infrastructures and equipment investments taking care of an efficient and reliable hinterland access [KP08]. In consequence the research in SND is of major importance for creating new transport solutions in the hinterland and supporting right decisions in such complex system.

### 2.2.1 Intermodal transport

The promotion and implementation of intermodal transport services enable a better use of the transport network, i.e. its modes and resources. The UNECE and the European Commission define intermodal transport as "Movement of goods (in one and the same loading unit or a vehicle) by successive modes of transport without handling of the goods themselves when changing modes" [Com] and in the context of combined transport and for policy purpose the definition is extended to "Intermodal

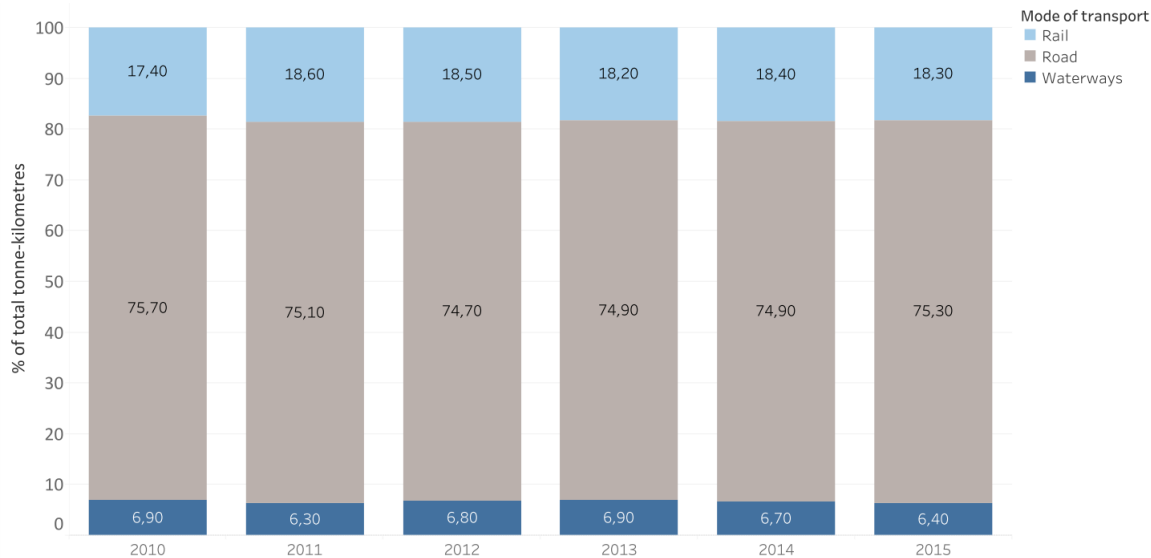


FIGURE 2.6: Modal split of inland transport in the EU-28 from 2010-2015 [Sta]

transport where the major part of the European journey is by rail, inland waterways or sea and any initial and/or final leg carried out by road are as short as possible" [Com].

Despite the efforts at policy level for an integrated and better balanced transport system in Europe, the modal split has only increased slightly in the past years. Despite of the modal split objectives set by the European Commission (as presented in chapter 1), road transport is currently still the dominant mode of inland transport in Europe accounting for over 75% of the volume of freight movements [Sta]. The other two inland modes of transport, rail and waterway, have increased their transport movements in terms of tonne per kilometer, but the share of modal split stagnates (Figure 2.6).

The flexibility of trucks in terms of speed and departure time, the broad road infrastructure together with the simplicity of execution of uni-modal transport (less actors involved and less need for coordination and planning) implies that road transport is the mode of transport often choose as first option for releasing the freight from the seaport to its hinterland. This tendency leads currently to undesirable environmental and social impacts with air and acoustic pollution, the increase of traffic congestion and overloading transport infrastructure not only in regions around the main seaport but all over Europe due to the high density population.

Intermodal transport is carried out since decades, but the complexity of operational transport processes hinders its implementation due to a lack of reliability and the need of several planing and coordination steps. Figure 2.7 exemplary presents the

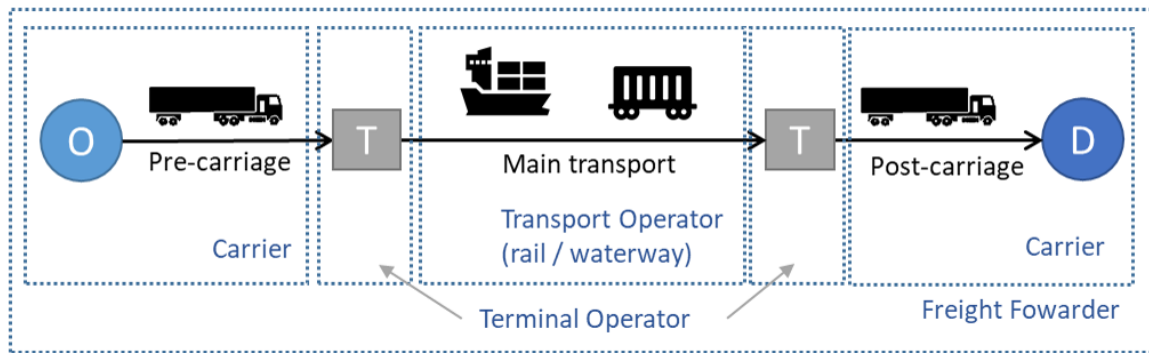


FIGURE 2.7: Actors within the intermodal transport chain

actors involved in an intermodal transport. Intermodal transport still represent a small portion of the total freight market [Sae+17] [Sta].

One of the reasons for the slow development of intermodal transport services are evolving freight customer needs and constantly changing priorities, whose fulfillment cannot be guaranteed when choosing intermodal transport. As Figure 2.8 indicates, the reliability of the transport service, i.e. the regularly fulfillment of transport agreements, delivering the goods efficiently, on time and intact, is the most important requirement for customers and the most relevant indicator when deciding for the selection of a transport service [Pfo18].

Furthermore the growing demand for faster product delivery in global and digital supply chains calls for more reliable, faster and flexible transportation services. The breakthrough innovations behind the fourth industrial revolution bring new possibilities for effective ways of cooperation under a connected and automated transport system. The transportation market is very competitive and intermodal freight transport has to use the potential behind the digitalization and new communication technologies for adapting and fulfilling the growing customers' needs (see Figure 2.8). The market needs new modes of operation to improve services' reliability and resilience with integrated intermodal services and an accurate information management of transport and logistics processes.

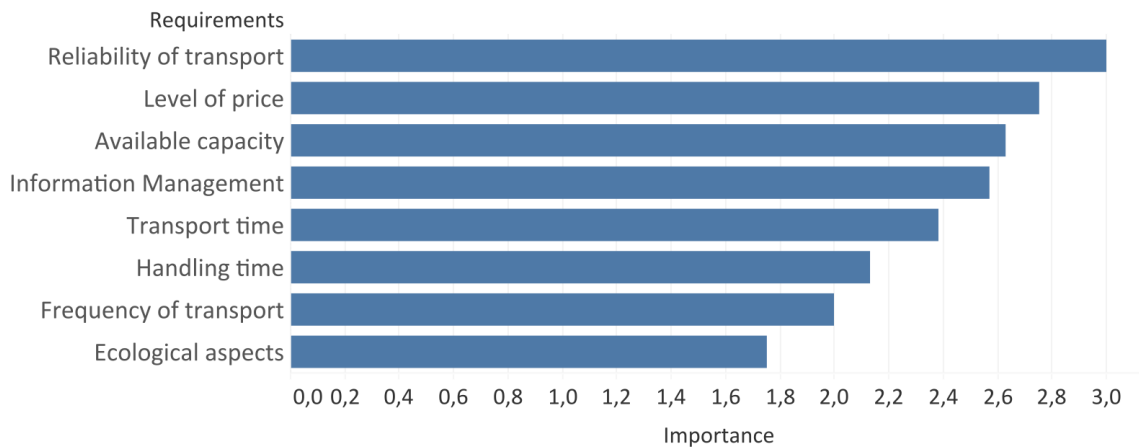


FIGURE 2.8: Freight costumers requirements for transport choice measured in importance level from 0 to 3 [ali]

## 2.2.2 Initiatives and action plans

The former Commission Vice-President responsible for transport, Jacques Barrot, defined the goals of transport in Europe as follows: “Europe needs efficient, integrated transport alternatives that are both environment-friendly and user-friendly. The integration of these modes of transport into efficient logistic chains is essential in order to reconcile the economic efficiency and long-term development of transport” ([ali]: 16)

Several initiatives and projects at a European level have been carried out with the aim of making freight transport more efficient and sustainable. These measures focused on logistics operations and the development of a rail network prioritizing freight transport, inland ports and maritime transport. The Commission proposed new initiatives in order to create an European freight-oriented transport network, in which the service had to be more reliable and more efficient.

One of these measures was the development of the TEN-T core network corridors addressing the improvement of physical transport connections and the reduction of bottle necks as well as setting standards for a better information flow [ali]. Figure 2.9 presents the current network with 11 corridors, of which three new corridors pass through Germany since 2014. In [Sae+17] a good and detailed overview of the current European intermodal freight transport market’s structure and network is given.

The logical next step is addressed in the current European Logistics Action Plan promoted by the Commission. The transport and logistic sector has "... to improve the flow of information accompanying the physical transport of goods, simplify administrative procedures, improve the competence and attractiveness of the logistics sector,

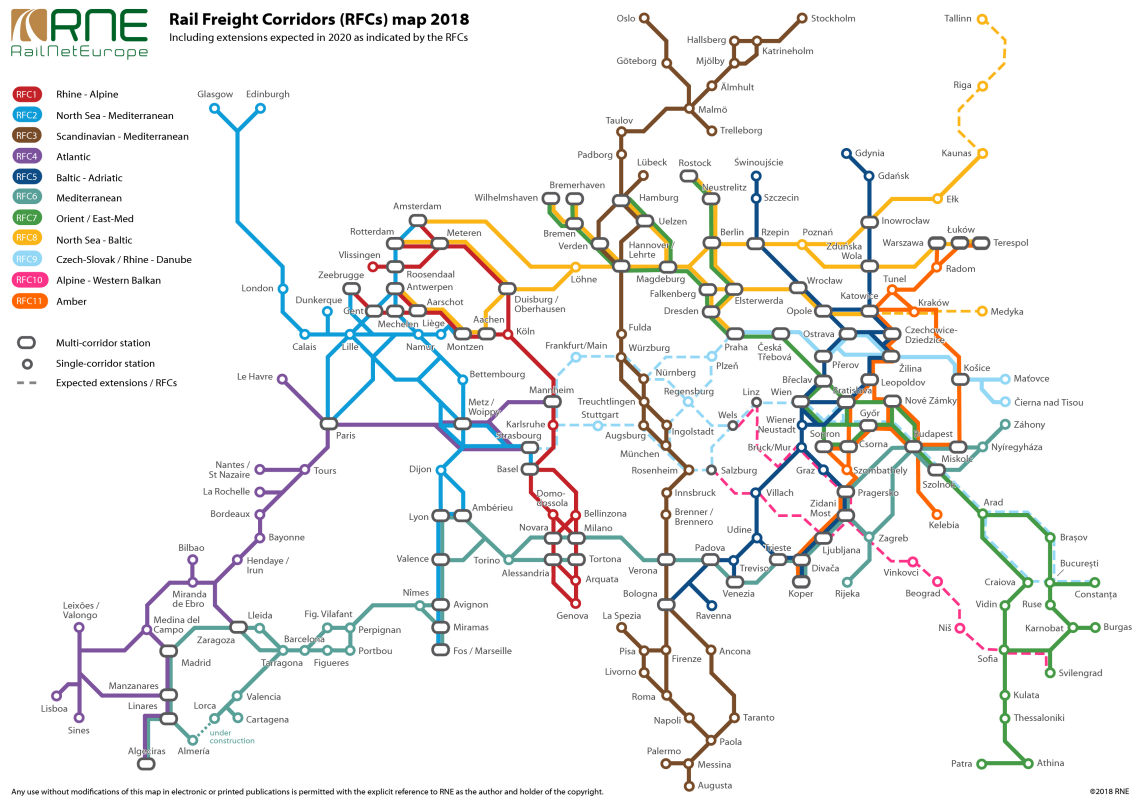


FIGURE 2.9: Ten-T corridor (c) RNE [RNE18]

and encourage high-quality services." ([ali]: 16). The commission summarizes the focus of current measures in six action fields [Eurb]:

- Use of ICT for the electronic flow of information
- Identification and analysis of bottlenecks
- Physical improvement of transport chains
- Adaptation of the regulation of weights and dimensions
- Development of green transport corridors
- Urban freight

At national level the development of a more efficient and integrated transport system has received also major attention in the past years. Germany presented their Freight Transport and Logistics Action divided in five focus fields in 2017:

- logistics and transport network
- transport infrastructure
- inter-connectivity of all modes of transport
- the promotion of environmentally friendly and energy-efficient freight transport

- the availability of qualified personnel and ensurement of good working conditions.

The document contains detailed information about taken actions as well as master plans for rail freight or strategy plans for sea and inland ports, for federal transport infrastructure or aviation [Fed]. Many other countries like The Netherlands [Min12] or Austria [bmv11] have developed similar on-going national master plans.

National master plans are of great importance, but assuring the integration of transport operations across national borders is still a key task of EU policies and crucial for the competitiveness of the whole European economy. A seamless transport in Europe is a challenge that needs to be addressed further. Following three aspects summarize the current state and the needs to achieve a cyber-physical transport network, i.e. "EU wide synchromodal services for a smart and seamless network, based on corridors and hubs, together facilitating efficient and effective supply chains" ([ali]: 11):

- There is currently an absence of common communication standards and operational processes as well as shortcomings in digital infrastructure. Standards for interoperability between digital infrastructure and a common language for communication processes have to be developed and implemented across Europe for a holistic integration of transport services and supply chain.
- Supporting information and communications technologies have to be highly reliable, affordable and as generic as possible to adapt to the necessity of all different stakeholders.
- The efficiency, flexibility and resilience of current supply chains increase by the visibility and collaboration capabilities of the transport network and its actors. Therefore the design of infrastructures and services as well as the operational control of the execution of transport processes should be optimized through an improved synchronization between their services.

This work has its motivation in the third point, but is depended at the same time on the establishment of the first two points as a basis. If little by little information and real-time access to the status and services of the transport network is gained, it is possible to generate greater flexibility and a better utilization of services in a shared manner, increasing the efficiency and the resilience of the transport network. To bring out this potential, models for the SND in synchromodal transport networks must be created.

### 2.2.3 Intermodal freight transport developments

Within the past years part of the research addressed the promotion of intermodal transport focused on the seamless physical connection, standardization, transshipment equipment and operational tasks between the different transport modes. An example for that research and the developments carried out in these areas are two European projects, TelliBox and TelliSys, which focused on the development of a new loading unit for intermodal transport meeting customer, mode and handling requirements [Hab13].

The project “Intelligent Transport System for Innovative Intermodal Freight Transport” (TelliSys) builds on the results of the preceding project TelliBox, “Intelligent MegaSwapBoxes for advanced Intermodal Transport”, which developed the first iteration of a new freight loading unit called MegaSwapBox (MSB), created for complying with the intermodal requirements. This new loading unit integrated the benefits of containers with the benefits of swap bodies, incorporating the market’s diverse requirements for intermodal loading units into one single concept [Fen14].

The research addressed the necessity to bring a system to the market, which is optimized for its intermodal transportation in Europe and efficiently increases the transport capacity, while complying with European transport policies and regulations. On the one hand, the common loading units for overseas and intermodal transport, the ISO-containers, are outperformed in terms of loading flexibility, volume capacity and costs by the road leading freight transport vehicle: the mega-trailer. On the other hand, current trailers are not designed for water or rail transport. Megatrailers, that can be craned, can be transported in freight trains with special wagons and weary handling processes. Besides, the extra weight for the wheel axes must be transported. To fill this gap, the TelliSys project designed a new intermodal transport system that combines the benefits of mega-trailers and multimodal containers.

A complete technology system composed by truck, chassis and LU, was developed for meeting the requirements of standardized transport processes and the requirements of users to optimize multimodal logistic chains in terms of transported capacity, for a more sustainable transport system [Fen16]. The goal of the project was to achieve a maximum load volume (up to 3 m internal height and  $100^3$  load volume) while keeping the overall height of trailer and load unit at 4 m. These aspects required the development of a new low deck tractor with 85 cm fifth wheel height and low dimension tyres for truck and trailer chassis [Tel16].

An extensive market analysis of the current status of European and intercontinental cargo transport standards helped to understand, how loading units and standard equipment are used from the numerous actors involved in the supply chain, including

TABLE 2.1: Family of intermodal loading units [Tel16] [Fen16]

Characteristics	Continental LU	Automotive LU	Intercontinental LU
Size	40 ft. / 45 ft.	45 ft.	40 ft. / 45 ft.
Height (internal)	2940 mm	2970 mm	2970 mm
Width (internal)	Euro-pallet	Euro-pallet	Euro-pallet
Long sides	One open	two open	closed
Payload	24 t	27 t	Min. 24 t
Roof	Hinged	Hinged	Hinged
Handling	Corner castings	Corner castings, grapples pockets	Corner castings, grapples pockets
Stackability	2 times	Not stackable	3 times

freight forwarders, manufacturers, ports, inland terminals and railway operators. In [Hab13] and [Tel16] a summary of main requirements for the intermodal LU can be found. Finally the decision was taken to create a family of tailor-made intermodal containers for specific markets (Table 2.1), all of them maximizing the volume capacity, while meeting intermodal standards for equipment and processes. The system was the first loading unit able to efficiently transport up to 100 m<sup>3</sup> by road, rail and water – enabling more efficient handling processes and increasing the intermodal transport capacity while being competitive against the leading road vehicle mega-trailer. With an internal height of up to 2,97 m and a flexible loading process from the side and the rear the Tellisys combination opens new market possibilities for costumers, who were forced to use road transport due to cargo dimension and/or costs benefits before this new transport combination became available. Figure 2.10 presents the TelliSys combination.

The efficiency of the new intermodal concept was analyzed in terms of costs savings and environmental impact. The results presented for a real scenario for an automobile manufacturer showed up to 15% of cost savings over the mega-trailers [Tel16]. More so, because TelliSys allows more volume of cargo to be transported in a single load, less trucks will be on the road. The system also had a significant positive impact on the environment, with a 25% reduction of Global Warming Potential (GWP) compared to current road transport technologies [Fen+16].

Two years after the closure of the project tellisys, loading units are on road [WEC17]. The 2,94 meter and 2,97 internal height loading units are being used successfully in international supply chains, specially for the automobile sector, due to their higher transport capacity and capability of transporting three standard gearboxes three times

stacked. This new transport system helps to increase the modal split in favor of rail or barge transport by enabling efficient intermodal transport of voluminous goods. Success stories like TelliBox and TelliSys help to overcome the resistance of stakeholders in the logistic sector against innovations threatening their traditional business models. Additionally, the physical and operational innovations improved the attractiveness of intermodal transport.



FIGURE 2.10: TelliSys combination

## 2.3 Synchronodal freight transport services

The development of new transport systems like TelliSys improves the efficiency in terms of costs and transport capacity of intermodal networks, while helping protecting the environment. But even if the reliability of the intermodal network is enhanced through smooth transshipment and flexible loading processes, the main challenges for successful intermodal services cannot be tackled by developing new hardware: The reliability and flexibility of train and barge services, as well as the cooperation between different transport mode operators.

The synchronodality platform created in the Netherlands with participation of logistic companies and supported by national institutions, defines synchronodality as "the optimally flexible and sustainable deployment of different modes of transport in a network under the direction of a logistics service provider, so that the customer (shipper or forwarder) is offered an integrated solution for his (inland) transport" ([vND15]: 2). Also, the European technology platform ALICE (Alliance for Logistics Innovation through Collaboration in Europe) encourages the integration of synchronodal services in intermodal transport by "synchronizing intermodal services between modes and with

shippers, aligning equipment and services on corridors and hubs and integrating these into networks" ([ali]: 3).

First test and praxis examples of a synchromodal network are given in the pilot study on synchromodality "Identification of bottlenecks and possibilities for a network between Rotterdam, Moerdijk and Tilburg" in 2012 [Luc12]. Further, positive experiences with the implementation of synchronized intermodal services exist "in port-hinterland container transport, in proprietary transport chains and in hybrid (dual-mode) supply chains of certain shippers" ([ali]: 11). However, these experiences offer a very limited choices of transport services, working with fixed routes or modes and without a real-time information background. In the current transport network a lack of services' synchronization between multimodal operations continuous to exist.

Therefore, within the H2020 research programme of the EU promoting of an smart, green and integrated transport, synchromodality is one of its research and implementation priorities [Eur17]. The creation of a synchromodal transport in Europe is already covered in some current EU H2020 projects. Most relevant ones contributing to the synchromodal field are SELIS - Shared European Logistics Intelligent Information Space [SEL16], AEOLIX - Architecture for EurOpean Logistics Information eXchange [AEO16], and SYNCHRO-NET - Synchro-modal Supply Chain Eco-Net [SN15].

At country level The Netherlands is leading the research in the field of synchromodality. The idea was born there and well-know research institutions are leading the research nowadays. For example, under the national *Synchromodal IT research program* the creation of an integrated synchromodal logistical network is pursued with the goal of increase the efficiency, reliability and sustainability of freight transport as well as achieve the required mental shift within LSP and cargo owners [Bol16].

The technologies and logistic approaches behind synchromodality need to spread wider to the whole supply chain. The Internet of Things (IoT) and Cyber Physical Systems (CPS) are two important concepts defining the changes imposed by the new technological developments. The concept of CPS is defined as "systems where virtual and real systems are linked closely at various levels and the components are networked at every scale" ([Jes+17a]: 7). The physical application of CPS corresponds to the term IoT, which can be described as an information network of physical objects (e.g. sensors, machines, cars, buildings, etc) that allows interaction and cooperation of these objects to reach common goals [AIM10].

As in the idea behind CPS, a synchromodal transport system, combines individual private networks (e.g. LSP or intermodal operators networks) into one global super-network allowing the combination of services of different providers [ali]. The increase

in the number of services and capacity results in a superior flexibility for the customer or planner, so that the best possible mode can be used at all times. When selecting a mode, demands made by the stakeholders on the service (e.g. time of delivery) must be fulfilled, keeping the global status of the transport network (e.g. condition of roads, availability of terminals) in mind. Due to its superior flexibility, a synchromodal network aims to respond faster and better to customer needs, increasing its resilience against unexpected changes and external conditions even further.

Within the Alice Roadmap for future European logistics [ali] six research areas were indicated until 2020: Development of data analytic in logistics, predicted methods for connecting demand and supply, the definition of synchromodal operation principles, define hub business model principles and ITS Logistics architecture for connected applications: operational (ITS), tactical (service design) and strategic (business intelligence). Besides following products are the objective for the next years (from 2018 to 2023) [ali]:

1. Developing forecasting methods for predicting synchromodal demand
2. Production and transport optimization.
3. Develop hub and cluster business models enabling cooperation between transport actors including pricing, rights,
4. EU freight network in TEN-T guidelines
5. Performance based a-modal transport planning and booking
6. Connected ITS and multimodal TMS applications for seamless transport information availability.

Some of these innovative transport and logistic products have been listed in the scientific literature, where the research questions behind them have been examined. [Table 2.2](#) presents latest papers discussing the concept of synchromodal transport. These papers discuss the synchromodal implementation requirements, challenges and benefits for all planning levels.

TABLE 2.2: Most recent scientific articles in the field of synchromodality focused on the implementation requirements

Contribution	Author
Literature based identification and definition of enablers and critical success factors for synchromodal transport	[PTS16]
Current research and opportunities in synchromodal transport. Focus on the topics of integrated and real-time network planning, and the creation of planning flexibility, for enabling synchromodal planning.	[vND15]
Synchromodal characteristics (pre-requisites), effects and current research	[SvW16]
Feasibility study, advantages, challenges and factors for synchromodal transport and a SWOT analysis for the case of Ghana.	[Agb+17]

As synchromodality affects the supply chain in several areas by linking tactical and operational planning level, it also offers many possibilities for improvement. But what are the prerequisites for synchromodal transport? In a literature review, Putz et al. and [Put+15] and Pfoser et al. [PTS16] identified following six interdependent areas:

1. network cooperation and trust,
2. sophisticated planning and simulation,
3. information, data and use of ICT and ITS,
4. physical infrastructure,
5. legal and policies issues,
6. awareness and mental shift and
7. cost, service and quality.

As the success of TelliSys has shown, a progress in one of the listed areas stimulates actors in the logistic sector to pursue the concept of synchromodal transport further by demonstrating, that the benefits promised by researchers can be obtained. Because of the interdependence of the areas, a success in a single area is not sufficient for a successful implementation of a synchromodal transport. In order to use resources better and more sustainable, which is in the end the underlying goal of synchromodality, advancements in all six areas must be made, enabling a vertical and horizontal cooperation of all involved actors (Compare [subsection 2.1.2](#)). The availability of real time data and information in the European transport and logistic sector reinforces this goal,

bearing the potential to revolutionize the field of transportation planning, execution and supply chain management [Fen17].

## 2.4 Summary

The enormous potential inherent to the concept of synchronomodality has been highlighted in this chapter. Synchronomodality implies a better coordination of transport services under the premise of an efficient utilization of transport resources and modes. This effect increases the resilience of the network, causes a better consolidation of loads and offers an increased flexibility by enabling free modal shift. Because of this potential, current initiatives and action plans are addressing the need to extend multimodal transportation models towards synchronomodal transport.

At the beginning of the chapter basic definitions and concepts have been introduced in order to expound today's challenges of the logistic sector. Most of the challenges take place at European level and need to be faced in a cooperative way. Especially the use of new technologies introduced by the 4.0 developments offers a great research potential regarding real time decisions on routes' choice, faster communication, information transparency between supply chain actors, and a better prediction of demand and needed transport network capacity.

The idea of synchronomodality builds on this technological advancements and cooperation and requires a well-informed network and flexible planning, booking and management, in order to allow mode and routing decisions at an individual shipment level, considering the best possibility given by the whole transport network at real time. This synchronization of the services enables, but also requires flexible and dynamic transport planning processes for reacting to unexpected conditions. Within the next chapter the state of art in planning models and optimization approaches for multimodal transportation are discussed.



## Chapter 3

# Analysis of freight transport modeling approaches

As discussed in [chapter 2](#), freight transportation is a key economical activity in every region of the world. This is reflected by the continuous growth of transport demand all over the world and the consequently continuous increasing number of carriers and LSPs [[Oe2](#)]. Freight transportation planning is crucial for the supply chain and ensures the efficient movement and timely availability of raw materials and finished goods [[Cra00](#)].

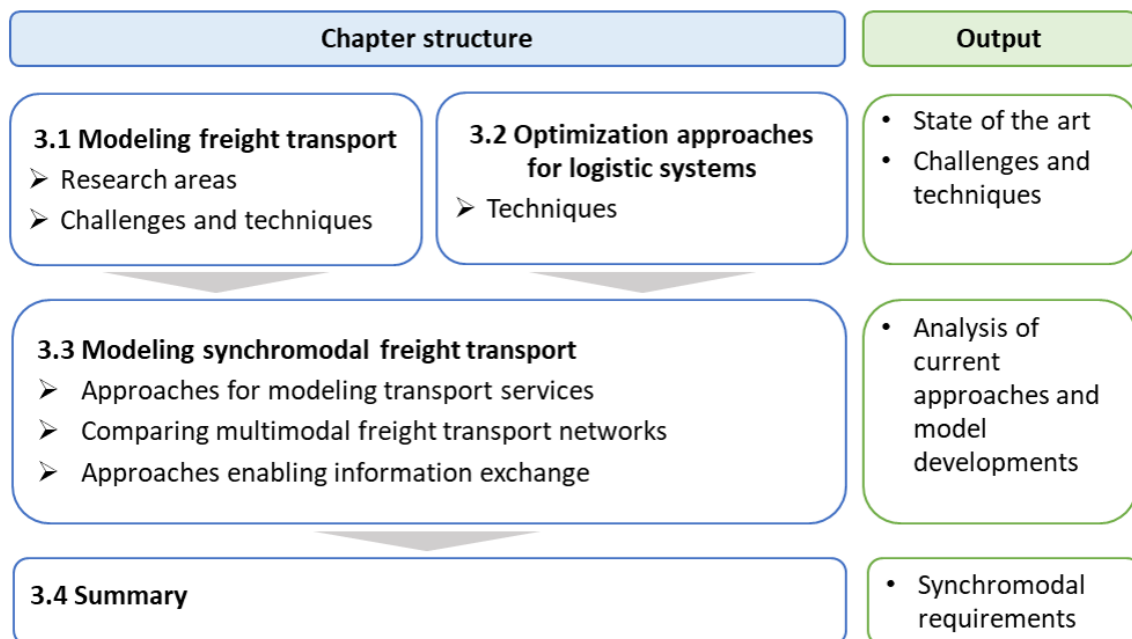


FIGURE 3.1: Chapter 3 structure and content flow

These aspects contribute to having a highly competitive sector where LSPs must adjust rapidly to changes in costumers' requirements, economy and policies while delivering high quality, reliable and low costs services. How can LSPs ensure their economical

success and at the same time collaborate for a sustainable transport system? The need to find the most convenient transport route and the design of efficient logistic services depends strongly on the design and current state of the whole transport system. Thus the analysis of freight transport systems and the development of transport models for decision support at all three planning levels are crucial for logistic actors, from manufacturing companies and LSPs to government entities.

Hence, this chapter presents the state of the art of current approaches analyzing, modeling and optimizing freight transport systems. Special focus is set on current literature, presenting the advances in synchromodality, defining requirements, approaches and tools for developing synchromodal transport models. [Figure 3.1](#) presents chapter's structure and content flow. A further focus of the chapter is the descriptive analysis of current models for simulating synchromodal networks. Finally the requirements for a model, which enables the analysis of complex and dynamic multimodal networks, will be delivered.

## 3.1 Modeling freight transport

A freight transport and logistic system refers to the equipment and logistic processes for supplying goods from origin to destination. An important component associated to a transport system is its transport network, which can be define as the framework of routes and transport modes linking transport nodes where freight is originated and destined [[Ree12](#)]. In reality, the nodes represent logistic infrastructure as intermodal terminals, hubs, warehouses or production and consumption places.

The design, management, planning and control of a real logistic system is characterized by many interactions between system components generating complex decision problems. The interactions between these system components characterize the design, management, planning and control of a real logistic system, generating complex decision problems. To support decision tasks, models are created describing the logistic system and enabling the simulation of different complex processes. As logistics deals with dynamic material and cargo flows within the supply chain, the representation and simulation of such flows is of major importance for a better planning and execution of freight transport.

In logistic systems the material flow is not constant on time and the cargo amount and demand is constantly changing, thus Material Flow Analysis (MFA) are essential for describing the complexity of the transport system. The OECD defines MFA as "the study of physical flows of natural resources and materials into, through and out of a

given system (usually the economy). It is based on methodically organized accounts in physical units, and uses the principle of mass balancing to analyze the relationships between material flows (including energy), human activities (including economic and trade developments) and environmental changes." - OECD 2008 [MM17].

A network model represents the transport infrastructure and service offered, i.e. the material flow from an origin to a destination through logistic nodes. In analogy to fluid dynamics the representation of flows consider an origin (source) and destination (sink) and a dynamic, i.e. time-varying, cargo flow. The logistic network is represented by the connection of all source and sink points (nodes). Lavoisier's principle of mass conservation is applied for understanding these movements, so that in each node the sum of all transport inflows is equal to the sum of all outflows. Thus the logistic network is abstracted to a network of nodes and arrows, where the flows represent transport processes while the nodes represent cargo collecting points like warehouses or terminals.

The modeling of transport and logistic systems is a field with some history, where firsts freight transport models appeared in the 1960s. Important technical developments started in the mid-1970s, but the attention remained in an academic context. The research on freight transportation evolved slower as on passenger transportation due to the public repercussion and the fact that public policy makers turned their attention much later to the freight transport area [TJ14]. Nowadays exists a better recognition of the role of freight transport modeling as an essential tool supporting transportation planning [OW11]. But still the praxis implementation of developed transport models and planning approaches remains at a theoretical level and the transfer to real use cases remains an open task [TJ14]. Some reasons are given to the complexity of the transport system, e.g. regarding the number of actors and their relations, the transferability of the models to specific logistic use cases and the lack of information transparency and digitization in complex logistic processes. This lack of transparency is caused at the same time by the high market competition, where logistic actors are leery of cooperating for fear of losing their market niche and share.

The creation of the European Union together with the opening of borders at European level brought the emergence of common transport policies. These policies fostered the development of holistic models at international level addressing new transport possibilities, trade and economic relations. A good overview on key transport policy issues in Europe and the associated decision problems and modeling needs can be found in [Tav]. After 10 years the key issues and modeling needs addressed in the article are still today in focus of research. Issues like the growing of transport demand, seamless multimodal networks, pricing, logistics performance, modifications in vehicle types

or environmental effects are main modeling needs in a continuous evolving transport framework.

The capabilities and focus of models evolved with the computer calculation capacities adapting to new research techniques and requirements coming from the society, companies or government. Two books on freight transportation modeling [TJ14] and [OW11] and one for transportation planning in general [Mey16] give a good overview of modeling approaches and steps. Modeling transport networks requires a high level of information, historical and up-to-date data as well as it also implies a large number of actors. The complexity of the logistic system with high variability and plenty of uncertainties causes a large gap between plan and execution.

Logistic models are created for modeling and evaluating complex transport and logistic processes, enabling a better understand of system interactions and thus supporting the solution of an specific decision problem. Figure 3.2 presents a conceptual framework of the freight transport system divided in four horizon levels and differentiate by the decision problem and the modeling challenges behind them. This overview focuses on the transport and logistic problems relevant for LSPs, manufacturers and planners sorted by time horizon. Focus of this chapter is the state of the art and approaches at the level of transportation and network services. Other decision problems regarding trade or the relation between production and consumption are not detailed here due to their strong strategical economic factor and temporal remoteness with service design decisions.

The four levels are divided by their planning time horizon, where the selection of network services has the decision problem with the shortest time horizon. As discussed in chapter 2, the synchronization of logistic and freight transport services and the integration of these in the SC will transform the time-dependency of tactical decisions. From this point forward, decisions regarding choice of mode, resources' disposition or routing are also taken at operational level (see marked zone in Figure 3.2). This means that these decisions are readjusted and customized depending on the real time situation.

## 3.2 Optimization approaches for planning logistic systems and processes

Within the logistic planning process a large amount of precise decisions must be taken, like number of resources, goods or the scheduling of transport vehicles, so that the

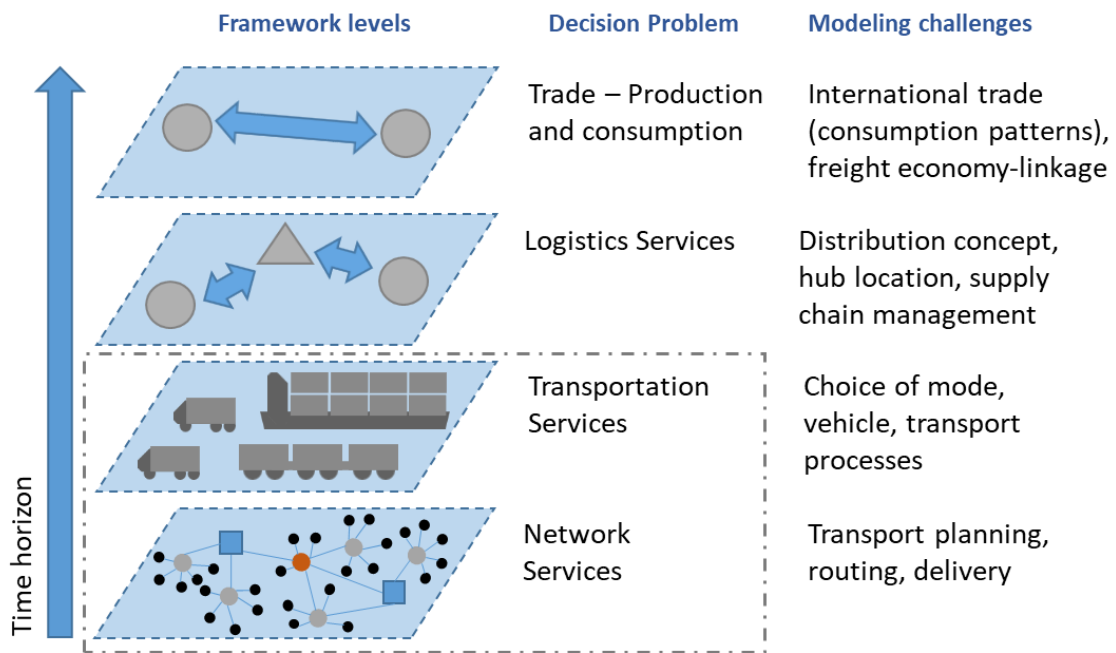


FIGURE 3.2: Freight transport modeling levels and challenges adapted from [Tav]

decision model must be quantitative. Depending on the complexity of the decision problem and the information available, the decision problem can be spitted according to [Arn08] in four types:

1. Deterministic one criteria optimization models: one objective function to be maximized or minimized.
2. Multi-criteria optimization models: more than one criteria to be considered simultaneously. In this case instead of one objective function a vector  $F(X) = (F1(x), F2(x), \dots)$  is created.
3. Individual optimal solution.
4. Stochastic optimization models.

The research field developing and applying scientific methods for the improvement of efficiency in operations, management and complex systems decisions is called operations research [C. 13]. Usually pursued goal is the achievement of a satisfactory optimum for an specific desired objective with an optimal utilization of available resources. The scientific modeling of the system to be investigated is required for simulating, predicting and comparing the results of different system states, strategies, decisions and relations between system's variables by incorporating probabilistic and risk measures [A. 10]. The modeling of logistic systems is crucial for supporting decisions within the management, planning and execution of transport and logistic processes.

In operations research model-supported optimization methods have been applied to solve a variety of complex decision problems. Classical optimization methods include methods like linear programming, mixed integer programming, non linear, stochastic or dynamic programming. On the other side those methods that mimic phenomena observed in nature and are related to the artificial intelligence concept can be grouped under the name of meta-heuristic methods. Meta-heuristic methods include evolutionary algorithm (EA), like genetic algorithms (GA), simulated annealing (SA) and heuristics search methods like Tabu search [E. 13].

Table 3.1 present an overview of optimization methods used in the logistic field based on [Arn08] and divided in three types of problem's complexity. Linear programming or optimization presents exact algorithms. Mixed integer programming (MIP) or combinatorial optimization is used for solving problems that cannot be efficiently (NP-hard) solved like the Traveling-Salesman-Problem (TSP) or the capacitated vehicle routing problem (CVRP)[T. 09]. Finally non linear programming are optimization problems presenting some nonlinear constraints of the objective function. In most of the cases these problems are solved through the splitting of the problem in linear functions, thus approximating the solution.

After this introduction, which has given an overview of general optimization approaches being used in the logistic field, an specific literature research on optimization approaches for multimodal transport planning is presented within the next lines. In the past years specific research in multimodal transportation planning has received an increased attention. The literature review from SteadiSeifi et al. on multimodal freight transportation planning covers the main approaches from 2005 to 2013 [Ste13]. An overview of the literature in the field of transportation planning and modeling covering publications up to 2005 is presented by Crainic in [CK07] [CGP09] [CLT06]. Both reviews categorize the research that has been carried out based on the three levels of planning horizon introduced in chapter 2 (strategic, tactical and operational). Models focusing on strategical planning problems are further classified regarding the type of allocation in single, multi or hierarchical allocation problems. Models for tactical planning problems are divided regarding their network focus: network flow planning, static service network design and dynamic service network design. Finally, models addressing the operational planning problem are divided in two types: fleet management and resource allocation problems on one hand and itinerary re-planning problems on the other hand. Besides, all transportation planning problems are also classified regarding their solution methodologies in exact, approximation, heuristics, meta-heuristics and hybrid heuristics.

TABLE 3.1: Overview of optimization approaches for planning logistic systems and processes

1 Linear optimization	
– Iterative exact algorithms	The Simplex algorithm is widely extended and operates with linear objective functions and convex problems.
– Graph theory and short path algorithms	The Dijkstra-Algorithm is an extended example for such algorithms based on a graph.
2 (Mixed) Integer programming (MIP)	
– Exact Methods	E.g. Branch and Bounds models for discrete and combinatorial optimization problems
– Heuristic Methods	Greedy approaches which maximize the optimum value for the previous partial solution
– Meta-heuristics	Approaches like Simulated Annealing, Tabu Search and Genetic Algorithm
3 Nonlinear optimization	
– Method of Lagrange multipliers	Defining Karush–Kuhn–Tucker conditions for finding a solution in nonlinear programming to be optimal

Similar to the conceptual framework developed by Tavasszy [Tav], the work of Crainic [CF14], reviews the optimization models for solving transportation planning problems and categorized them in three categories:

1. Strategic planning of multimodal systems: multimodal multi-product goods transport network planning models.
2. Network balancing models: This category includes traffic assignment models and transit route choice models. Traffic assignment models are used to describe users traffic flows and route choices on congested networks, while transit route choice models are used to analyze the design of transport service's frequency.
3. Spatial interactions models: Also known as trip demand distribution networks, these models are used to explore demand patterns between a given set of origins

and destinations.

Derived from these two above presented classifications for multimodal transport planning problem levels, the core focus of this work, a synchronomodal planning, involved following transportation planning problems:

1. Service network design (SND) problem
2. Resource allocation problem
3. Itinerary re-planning and routing problems

These problems belong to tactical and operational planning problems dealing with decision problems about transportation and logistic services. As described in chapter 3.1, routing planning is an important part of every transport model. A review of route optimization models in multimodal transportation networks can be found in [Behri], concluding that only a limited amount of studies focus on this topic. Besides, these studies mainly used the Dijkstra shortest path algorithm with basic constraints to identify optimal routes.

In [CF14] an overview of most used traffic assignment models and algorithms is described. However the application scenarios make reference to passengers transport planning, thus only a few concepts can be transferred to the synchronomodal planning problem. For example, to analysis of temporal traffic problems, where the demand has to be quantified at a given fixed time. In this case, the network model takes the form of a static network (variational inequality optimization problem) using a starting point for calculating the flows between a given set of nodes (origins and destinations pairs) under consideration of the defined transport infrastructure and services offered [CF14].

Furthermore a number of scientific articles focusing on modeling freight transport systems with different objectives and at different levels have been published in the past years, showing the importance of the topic [Behri], [Le 16], [HT17], [Dav15] or [Tav96]. Most recent models will be analyzed and discussed in detail within the coming sub-chapter.

### 3.3 Synchronomodal freight transportation models

Synchronomodality demands new models and approaches for creating flexible and efficient transport planning. As discussed in section 2.3, the implementation of a synchronomodal transport service influence two decision areas, the tactical and the operational.

Therefore, new planning problems like the dynamic service network design, flexible resource allocation and itinerary re-planning problems have to be solved under new sychromodal assumptions and constrains.

Within the last few years, the amount of research publications discussing and addressing the idea of multimodal transport network with sychromodal characteristics have increased extremely. SteadieSeifi et al. [Ste13] presents an extensive literature review on multimodal freight transportation planning until 2013 and discusses the idea of sychromodality. Furthermore, Sun et al. [SLW15] provides a review and categorization of optimization models and solution algorithms for freight routing planning problem in multimodal transportation networks, focusing on the mathematical description and characteristics of such models and algorithms.

Table 3.2, Table 3.3 and Table 3.4 give an overview of the most recent scientific articles in the field of modeling multimodal networks with sychromodal characteristics from 2013 until today. This literature review on sychromodal freight transport covers two different categories, depending on the paper's focus and field of contribution. Table 3.2 presents papers focusing on sychromodal transport modeling, planning and control. Furthermore, the literature review summarized in Table 3.4 analyzes the benefits of implementing information and communication technologies in sychromodal transport networks. To gain a better overview of the different models developed within the last years, the articles are further classified regarding their planning decision horizon [Fen18]:

- The strategical planning focuses on long-term transportation investment decisions, like the design of infrastructure or the purchasing of equipment.
- The tactical planning focuses on the SND, considering available transport infrastructure, modes and their capacity, so that decisions regarding the planning of services' frequency and vehicles' itinerary can be taken.
- The operational planning deals with all (near) real-time requirements in a multimodal transport network, e.g. the best route selection or the optimal cargo allocation considering actual demand and available transport services.

### 3.3.1 Approaches for modeling sychromodal transportation services

The modeling of sychromodal transportation services is based on the research carried out in multimodal freight transportation. Within a sychromodal network near to real time container routing and cargo flows are of major importance. However, the

TABLE 3.2: Most recent scientific articles in the field of synchromodality focused on the modeling, based on [Fen18]

Contribution	Planning level	Author
A multi-agent-based model for simulation of transport chains with physical and decision-making simulators. Mathematical definition of actors and definition of interaction protocols. Goal: analyze transportation chain effects. Implementation in Java programming language.	Strategic	[Hol+12]
Mathematical model for the tactical service network design for an intermodal container network. Main characteristics: capacitated and multimodal network with flexible due dates and the possibility of using subcontracted transport. Goal: minimize transport costs. Implementation in Cplex®.	Tactical	[van+13]
A cooperative framework for freight distribution in multimodal corridors and model for optimizing distributed supply chain using a decentralized approach. Goal: determine best scheduling plan. Implementation in Matlab® and Cplex®.	Tactical	[DSS13]
Linear container allocation model with time-restrictions for a global cost-effective container transportation planning solution. Goal: impact and relevance of network disturbance.	Operational	[van+14]
Mathematical model for designing integrated service schedules in synchromodal freight transport networks. The output of the optimization model is the service departure time and the flow of batches transported by each service.	Tactical	[Beh+14]
Multimode multi-commodity network design model for intermodal freight transportation with transfer and emission costs. Test use case for United Kingdom.	Tactical	[QBB14]
Model and algorithm for container allocation problem in synchromodal transportation.	Tactical	[Xu+15]
Green intermodal service network design with travel time uncertainty.	Tactical	[Dem+15]
Mathematical formulation and algorithm of a synchromodal model (SynchroMO). Modeling of synchromodal services with demand generator, network representation and schedule-based flow assignment.	Operational	[ZP16a]
Service and transfer selection for freight in a synchromodal network	Tactical	[PM16]
Cooperative synchromodal freight transport model for predictive container flow control problem.	Tactical	[LNS16]
Real-time container transport planning with decision trees based on offline obtained optimal solutions.	Operational	[vND16]

research of container routing and container flows in intermodal networks was based on rather isolated approaches until 2010 [CMJ13] [CKC12] [van13]. Within this section an overview of the most recent scientific articles describing and evaluating models and algorithms for multimodal transport networks from 2013 onwards is presented. **Table 3.2** present the studies focused on the modeling of multimodal transport networks for better planning and simulation of synchromodal services control. Although limited to synchromodality, a variety of modeling and optimization objectives can be found: from strategical infrastructure planning to vehicle scheduling or cargo assignment. Each of the listed studies focuses in slightly different situations and context, thus considering different constrains and assumption for modeling the transport network. Furthermore, some of them evaluate the created models analyzing the implementation of synchromodal services in specific regions and for different use cases.

Two objectives have been especially in focus of the research in the past years. On one side, the research question of developing optimal service network design at strategical and tactical level has been of importance. This includes the determination of services' schedules and the network design from the necessity of building new connections to the construction of new strategical infrastructure. On the other side, some of the presented work focuses on the development of modeling approaches supporting the decision problem of container allocation and flow assignment from a operational and tactical perspective.

The reviewed literature shows that tactical models have focused on the modeling of optimal scheduling of synchromodal services, e.g. vehicles departure times considering and modeling the freight demand, either in a random way [Xu+15] or heuristic based predictive demand [vND16]. In [LNS16] the distributed model predictive control approach is used for controlling synchromodal network service design. On the other side, operative synchromodal models and tools dealt with near to real time assignment of orders and resource management decisions.

In order to analyze the differences between the above presented modeling approaches, the works contributing and focusing on a dynamic, multimodal service network design are compared in detail. The corresponding six papers are analyzed considering the following characteristics:

- The main objective of the optimization problem.
- The transportation case: deterministic or stochastic.
- The programming tool: software or programming language and the optimization problem that has been solved.

- Modeling approach and assumptions regarding time concerns (fix schedules, flexible time with penalties or schedule with time windows), the modeling of environmental impact and monetary costs.

The results of this comparison can be found in [Table 3.3](#). The analysis shows that the different synchronodal aspects have been modeled in the past with different granularity and assumptions. The synchronodal hinterland freight transport model from [\[ZP16a\]](#) is the first work considering the critical features for synchronodal transport planning jointly in a model. This model admits a comparative analysis of intermodal and synchronodal operations considering environmental and economical aspects. The model is composed by a module for demand generation, a module for super-network representation and a module for capacitated schedule-based flow assignment. The authors generate 24h-demands synthetic data set based on annual level demand profiles using Monte Carlo as stochastic sampling procedure. The assignment procedure follows a FIFO approach where shipment orders are sorted by their release timestamp, so that they are incrementally assigned to the cheapest route with remaining capacity. The routing follows a shortest path approach.

In [\[van+13\]](#) and [\[van+14\]](#) a linear container allocation model with time-restriction is developed to obtain best transport routes, following different FIFO and greedy approaches [\[Qiu17\]](#). This container allocation model is used by [\[vND16\]](#) for developing a faster decision tree model with the goal of forecasting best assignments of orders.

Behdani et al [\[Beh+14\]](#) and Qu et al. [\[QBB14\]](#) focus on the service network design problem. They developed different methods representing a multimodal network for synchronodal freight transport systems with the common objective of defining service schedules. Demir et al. [\[Dem+15\]](#) present a capacitated multimodal transport network model, created to analyze time aspects in a synchronodal SND. Finally in Perez Rivera et al. [\[PM16\]](#) a Markov Decision Process (MDP) model is developed for service and transfer decision selection in a synchronodal network over time and with uncertain demand.

### 3.3.2 Approaches enabling information exchange

Among others, two important aspects have been mention in [chapter 2](#) as enabler for a synchronodal transport network: the network cooperation and the use of ICT and ITS. Within the first part of this sub-chapter the focus has been set on presenting the current state of the art in sophisticated models for planning and simulation. However, these models can only be useful if they are implemented for a real synchronodal network. Therefore the acquisition of transport and logistic data is indispensable in

TABLE 3.3: Comparison synchronomodal models for service design and container assignment, adapted from [Fen18]

Contribution	Optimization problem	Transportation case	Programming model	Time concerns	Env. impact modelling	Costs modeling
[van+13] [van+14] [vND16]	Real time container allocation in a network	Deterministic and stochastic	Linear integer (CPlex) and decision trees	Flexible (penalties)	No	Detailed (fix costs, per service, and handling)
[Beh+14]	Operational re-sourcing scheduling (small network)	Single commodity; Deterministic	Linear integer	Flexible (penalties)	No	Unit transport cost per mode
[QBB14]	Network design with assignment of vehicles to links	Multi-commodity; Deterministic	Non-linear integer (CPlex)	Fix schedules	Function of distance and weight	Detailed (variable per weight unit)
[Xu+15]	Container capacity allocation for carriers	Stochastic with random demand	Stochastic integer (C plusplus)	No	No	Fix route profit per freight type
[Dem+15]	Service numbers and network design	Deterministic and stochastic	Linear mixed integer (CPlex)	Flexible (penalties)	Detailed model	Costs per container and service
[ZP16a] [ZP16b]	Capacitated schedule-based flow assignment	Deterministic and stochastic, time varying demand	Transcad	Fix schedules, time track	Function of vehicle type, load and speed	Detailed based on haulage, handling process...
[PM16]	Dynamic service and transfer selection	Stochastic	Approximate dynamic programming	Schedules with time window	No	Direct and handling costs

TABLE 3.4: Most recent scientific articles in the field of information technologies for multimodal transport

Contribution	Planning level	Author
Discuss the dynamic and synchromodal container consolidation possibilities through cloud computing. Use case of Piraeus container terminal.	Alllevels	[Tse+16]
Tool for continuously assess alternative modes of transport in terms of time, costs and emissions. Test use case for Piraeus container terminal	Operational/Tactical	[KPS16]
Architecture and data model for cargo tracking in synchromodal logistics	Operational	[Raa+16]
Big Data interoperability challenges in logistics	Alllevels	[ZDM16]
Synchromodal control tower application architecture for transport planning	Tactical	[MI16]

order to support (near to) real time decisions in synchromodal networks. Since the idea of synchromodal transport is young, the literature found on this topic is rather limited. In Wan et al. [Wan+16] current research on and application of big data analytics in the field of logistics and supply chain management is given. Table 3.4 presents currently developed approaches for information exchange enabling the necessary information transparency for the creation of synchromodal transport.

Zelm. et al. discuss in their paper the challenges regarding big data interoperability within logistics [ZDM16]. To enable the information exchange between transport actors and to profit from big data analysis, data must be acquired, integrated, analysed and visualized. The tasks to be performed behind the data analysis pipeline are exemplarily represented in Figure 3.3. Within the logistic sector lot of effort in the digitization of transport relevant documents must still be made. To facilitate the step from data acquisition to its enrichment and modeling, Raap et al. present a logistic integration platform and discuss a common data model enabling the communication between different stakeholder's systems [Bol16] [Raa+16]. Tsertou et al. discuss also the possibilities of cloud computing for synchromodal transport at the Piraeus Container Terminal [Tse+16]. Finally Kapetanidis et al. presents an exemplary small implementation of a synchromodal decision support tool also for Piraeus container terminal [KPS16].

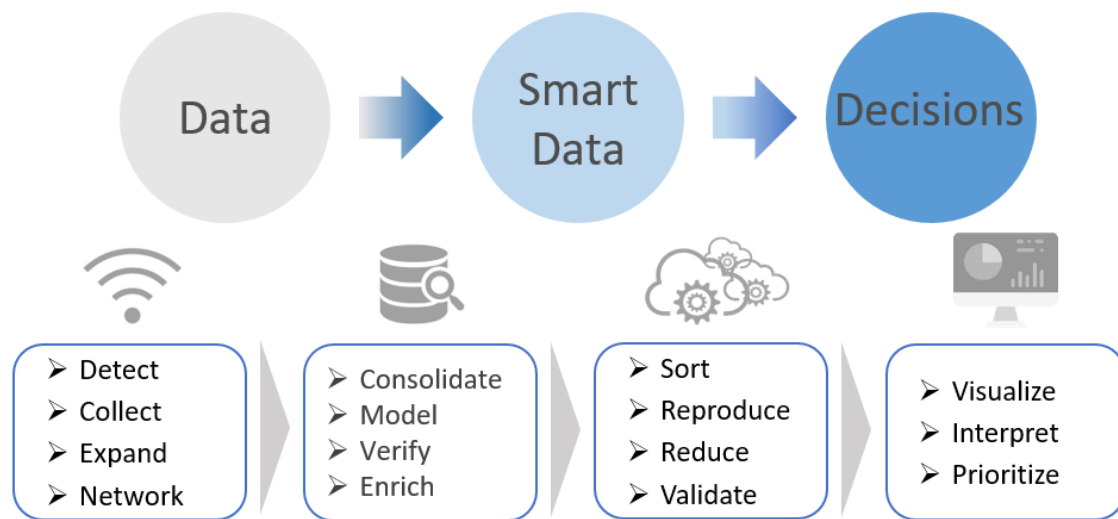


FIGURE 3.3: Data analysis pipeline based on [Jes17]

## 3.4 Summary

This chapter has presented the state of the art of current research on freight transportation planning, on service network design for multimodal freight transport networks and on optimization routing algorithms. Each category is used in the subsequent chapters to pursue the goal of this work: The optimization of the service network design and routing in intermodal freight transport networks with synchromodal services.

After the large review of projects, studies and optimization and planning models for synchromodal logistic in [chapter 2](#) and [chapter 3](#), the characteristics of synchromodal transport are summarized in [Table 3.5](#). These characteristics are extended with further model implementation requirements. The five derived transport and model implementation requirements for the European network are defined based on the different aspects, that have been modeled by the works presented in [Table 3.3](#).

TABLE 3.5: Synchromodal main characteristics and requirements  
[Fen18]

Characteristics	Implementation requirements
1- Real time switching between transport modes.	1- Dynamic transport planning: unforeseen shipments have to be planned in a short time; thereby synchromodal models have to deal with such uncertainties.
2- Optimal transport multimodal network resources utilization.	2- Capacitated transport network: modeling optimal capacity distribution between different transport vehicles (truck, train, and barge) and modes (road, rail and waterway) and an optimal terminal utilization will be modeled considering the capacity of the real network and service providers.
3- Free transport booking mode.	3- Multi-commodity and multi-stakeholders.
4- Cooperation between transport actors: shippers, carriers, logistics service provider, infrastructure operators, etc.	4- Real time network information, transparency and data exchange.
5- Real time optimization and service network design	5- Transport optimization of single units (containers) for the global network (all freight).

With the continuous improvement of computer calculations capacities, modeling approaches have increase in their complexity and efficacy. Thus, simulating and planning synchronized transport services demands new transport planning models that allow a dynamic transport planning with optimize routing for single loading units and flexible transport services.

## Chapter 4

# Synchromodal transport model

LSP as well as transport planners have to deal with high variability and fast changes in transport demand and transport supply. They have to dynamically adapt their services and strategies guaranteeing costumers', process's and products' requirements. In a synchromodal network the relation between planning the schedules of services, their capacities, controlling resources' disposition and the assignment of cargo would be even closer than in intermodal transport nowadays.

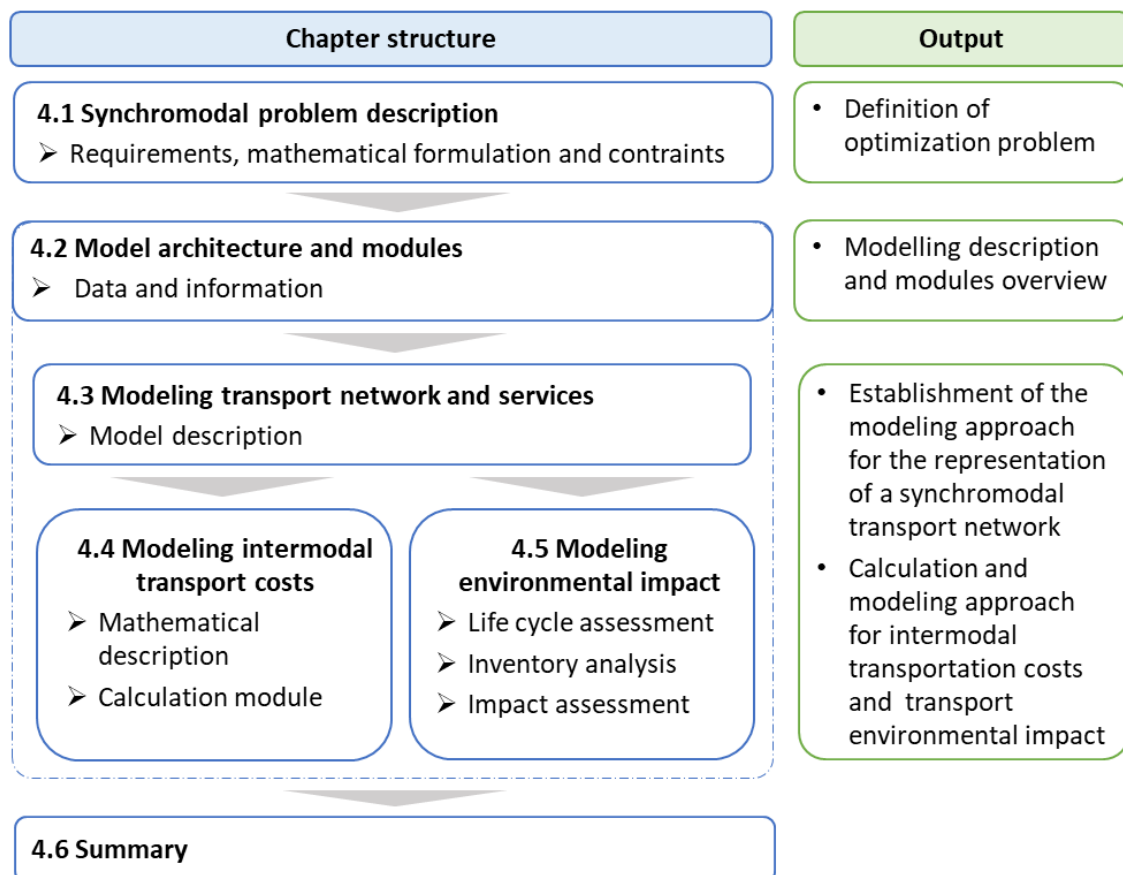


FIGURE 4.1: Chapter 4 structure and content flow

Synchromodality needs dynamic and near to real-time logistics decision support tools addressing optimal solutions, for example at service scheduling or container assignment level. The optimal solution is characterized by minimizing logistic cost, being environmental friendly and increasing the global performance of the network.

This chapter presents a quantitative intermodal transport model for simulating synchromodal services. Focus of the model is the delivery of different optimization approaches for container assignment, scheduling of services and transport capacities. The parameterization of the model allows the simulation of different scenarios and its adaptation for different use cases.

**Figure 4.1** presents the chapter's structure and content flow. Focus of this chapter is the modeling of an synchromodal transport network enabling the simulation of different operational cargo assignment strategies while studying and evaluating generated intermodal costs and environmental impact. The overall goal is to achieve a global optimum when deciding on the cargo assignment within a synchromodal network. The results of the analysis of current modeling approaches, presented in **chapter 3**, together with the requirements for enabling synchromodal transport presented in **chapter 2** are used to define the structure and the steps of the model that has been developed.

Later, in **chapter 5**, the analysis of possible actions and alternatives regarding transportation planning strategies will be presented and within **chapter 6** the results of modeling and optimization will be evaluated through different application scenarios.

The modeling of the transport impact and its assessment is divided in two main modules: The calculation of transport costs and the assessment of the environmental impact. The models created for this transport assessment are presented in the respective subchapters 4.4 and 4.5.

## 4.1 Synchromodal problem description

As seen in **chapter 2**, the research field covering the Service Network Design (SND) deals with the simulation of transportation flows supporting the tactical and operational decision process. Cargo is moved within intermodal transport networks using all three available ground transport modes. Transport services using rail and waterway as mode of transport are in most of the cases scheduled, while road services have the large advantage of being flexible in time. Thus in intermodal networks SND needs to offer a methodology for modeling more than one mode including their services' schedules, the representation of transshipment operations and the possibility to consolidate the freight inside the transport network [Dem+15].

The model presented in this work is created to fulfill the requirements defined in [Table 3.5](#) as stated above. The model is capable of dynamically simulate a current intermodal transport network, its services and offers sychromodal transportation planning including routing and scheduling of customers' transportation orders. The goal is to support the selection of available transport services providing an optimal cargo assignment.

A transport network is denoted by it transport services, connecting the different nodes (origins and destination) within an schedule and fixed itinerary. A transport service is characterized by its origin, destination, route, transportation mode, service capacity as well as start and end time and represents the connection between two intermodal terminals. It does not consider intermediate terminals or stops, so that a cargo transshipment can only occur at the start or end terminal. This definition of a transport service follows the one given by [\[Ste13\]](#) and [\[Dem+15\]](#).

Customers' transportation orders represent a pool of shipments to be transported within an intermodal transport network. They are characterized by the amount of cargo, measured in TEUs or number of containers, to be moved from origin to destination within a specified time window. The transport of a customer order can only start after the shipment becomes available and it must arrive at the final destination before its due date. The model allows to set a flexible time window for shipment orders, enabling a later due date i.e. a delay of cargo.

As presented in [chapter 3](#), the interest on dynamic SND methodologies has increased in the past years. Nevertheless the research on dynamic SND problems is still in its early stages, lacking of real applications and methodologies for service network environments [\[Dem+15\]](#). Besides, the reliability of transport planning optimization models limits their use in real situations. Thus, transportation models are considering time-dependent variables, e.g. in vehicle routing problems [\[CWO09\]](#), for better simulating the uncertainties within the transportation planning, like traffic congestion. Two types of uncertainties can be named in service network environments relevant for an accurate routing plan: The demand uncertainty and travel time uncertainties as described e.g. in [\[Bai+14\]](#) and [\[SWL17\]](#).

Thus the work presented here addresses the development of a capacitated multi-commodity service network design model including detailed monetary and environment impact costs as well as it takes into account uncertainties in transport demand. The focus is set in supporting a global optimal selection of available intermodal transport services for a given set of transport orders. The most efficient distribution for the whole network for in-coming orders guaranties an efficient cargo flow and an optimal routing while respecting the service's capacities and schedules. The objectives

of the optimization can vary depending on the consideration and importance of the environmental impact.

### 4.1.1 Model specifications

In order to optimize the utilization of transport network' resources and simulate a synchromodal network with flexible cargo flow and optimal routing planning, an optimization model is developed. Taking into account the requirements for the creation of a synchromodal transport network presented in [Table 3.5](#), the specifications of the synchromodal optimization model are defined in this section following the classification given in [\[SLW15\]](#):

- **Optimization object:** The optimization object considers multiple commodities with multiple origin-destination pairs. The assignment of cargo within the transport network assumes multiple transport operator services. The term multiple commodities means that different types of cargo will be considered when calculating the transport impact in terms of costs and environmental impact, e.g. through the use of reefer containers.
- **Commodity integrity:** The simulation of cargo flow considers splittable commodity. This means that the model enable the assignment of cargo from a unitary perspective, allowing the assignment of customers' orders, defined by their number of containers, but also allowing the optimization of the network utilization by considering each container as an unitary order. Thus a transport order can be split to achieve an optimal cargo distribution, while keeping customer's requirements, like maximum arrival time.
- **Transportation service pattern:** The model considers multiple transportation service patterns where the commodity transport follows scheduled based transport services. Within a synchromodal transport network the freight transport routing planning must solved the connection between multiple multimodal service patterns.
- **Optimization criteria:** The optimization criteria must have multiple objectives. Two global challenges can be addressed by creating synchromodal networks: a better utilization of network resources, guaranteeing a global optimum from monetary perspective as well as environmental impact perspective. Thus two objectives will be separately, within the single optimization, and simultaneously, within the multi-objective optimization, addressed: (1) minimize monetary

costs from a global perspective and (2) minimize the global transport environmental impact. Both criteria implicitly fulfill that a resource will be efficiently used looking for a global network optimization.

- **Transportation case:** The model will contain deterministic values fixed by the current state of services, e.g. service's capacity or time schedule, or by the use of average values, e.g. distances. However, in order to simulate the uncertainties happening within transport and logistic processes a stochastic transportation case should be considered. The consideration of such uncertainties increases the reliability of the solutions. Stochastic values can be considered for travel time and service schedules (e.g. taking into account the probability of delay due to network congestion) as well as for the variability in transport demand.

All these model specifications ensure the development of a synchromodal model addressing the simulation of a dynamic transport planning, that enables the routing of single loading units and the simulation of flexible transport services. In the next sections the model will be extended in order to address the challenge of an optimal assignment and routing of containers within an integrated network.

### 4.1.2 Modeling constraints and assumptions

The model is formulated under the following assumptions:

1. The model considers the synchromodal transport system defined by different intermodal transport services, using barge, rail or truck. Each service has its own cost, capacity and schedule.
2. The transshipment of containers can only occur in a node at the start or the end of a service, thus a transfer between modes does not occur during a service transportation. A fixed average value for a minimum transshipment time is considered for all mode changes and this transshipment service is always available. However a maximum transshipment time is not defined, thus an order can wait in a terminal for its next transport service. The transshipment's costs depend on the cargo weight.
3. The capacity of all three modes is limited. However, the model offers the possibility to set a flexibility parameter for selected services, where an extra capacity is defined.

4. Barge and rail services are defined with fixed schedules. Truck services have time flexible departures and arrivals, thus the time availability of truck services is always considered.
5. The duration of a service is given in the case of barge and rail by their schedule. For truck services the road distance and an average velocity of 60 km/h are used to calculate the transport duration. This duration is defined by the service so that it can be easily adapted to reality in cases where this average does not apply.
6. The management of a multiple vehicle fleet is not a focus of the model. The model assumes that each transport service is characterized by a different vehicle, thus a change in a transport service within a transshipment point will always represent a physical change of transport vehicles. Therefore time and costs will always be calculated at a transshipment point.
7. Orders are defined by their origin, destination, time window or transport interval and the number of TEU to be transported. The customer can select a latest time of arrival, providing a certain time flexibility to the order.
8. The model is designed for selecting the optimal combination of transport services within the order's time window, thus earlier arrivals at a destination are allowed. Earlier cargo availability or later arrival at the destination are not allowed, except for flexible orders.
9. The model uses the customer transportation demand as input, so that the total network demand at a given time is always known. Besides, the free capacity of all services is known as well.

The model is created to assign customer orders in a short period of time, especially when the services are already partially booked with contractual and regular shipments. Thus the output of the model is an optimal routing and service selection using the remaining free transport capacity. The flexibility options will supports the simulation of possible savings and resource's efficiency improvements when enabling more service capacity or a larger transport time window.

### 4.1.3 Mathematical formulation

As in all optimization problems, the presented synchromodal model is composed by system variables, a set of constrains and an objective function or two objective functions when considering the multi-objective optimization problem. The objective function

must be optimized as it represents a quantitative performance measure of a system. In this work, the goal of the objective function of the sychromodal model is to minimize the global impact costs. The model's variables represent the decisions that can be taken and will influence the value of the objective function. Finally, the problem's restrictions represent the set of relationships that certain variables have to satisfy. These relations and constrains are mathematically formulated in this section through the model's equations.

TABLE 4.1: Variables for the optimization problem

Variables	Description
$X^{so}$	Number of containers of order $o$ carried by service $s$
$C^s$	Monetary costs for service $s$ per container calculated using costs model
$E^s$	Environmental impact of service $s$ per container calculated using impact model
$C_T$	Monetary costs for a container transshipment
$T_e$	Environmental impact of container transshipment
$T_t$	Transshipment time duration
$T^o$	Number of transshipments for order $o$
$T^{max}$	Maximum number of transshipments for an order
$n_j$	Number of container transshipments done at terminal $j$
$t_d^s$	Departure time of service $s$
$t_a^s$	Arrival time of service $s$
$m^s$	Transport mode for service $s$
$R^s$	Duration of service $s$
$q_p^s$	Capacity planned for service $s$
$q_f^s$	Maximum flexible capacity for service $s$
$d^o$	Container demand of order $o$
$\tau_d^o$	Available time of order $o$
$\tau_a^o$	Arrival time of order $o$
$\tau_f^o$	Latest flexible arrival time of order $o$
$w_e$	Weight factor for denoting the influence of the environmental impact

TABLE 4.2: Mathematical description of data set

Data sets	Description
$O$	Set of transportation orders
$S$	Set of transportation services
$N$	Set of transshipment nodes

Table 4.1 presents all variables and parameters used to describe the mathematical problem, while Table 4.2 presents the data sets utilized for modeling the optimization problem.

The intermodal transport network  $N$  is represented by its transport services  $s \in S$ . These services are scheduled based and represent the free slots within the nodes  $i, j \in N$ . Each service connects the origin of the service  $i$  with the transshipment location  $j$  and is characterized by its schedule, departure time  $t_d^s$  and arrival time  $t_a^s$ , its mode of transport  $m^s$ , duration  $R^s$ , its capacity  $q_*^s$  ( $q_p^s$  and  $q_f^s$ ) its price  $C^s$  per slot (i.e per container or TEU) and finally its environmental impact per slot  $e^s$ . The service  $u$  denotes a succeeding transport service, while  $k$  the preceding transport service. As described in 4.1.2 truck services have time flexible departures and arrivals, thus when the transport vehicle of a service,  $m^s$ , is truck, than  $t_d^s$  is for the first transport service equal to  $\tau_d^o$  while for succeeding transport services  $t_d^s$  is equal to  $t_a^k$ .

Customer' orders  $o \in O$  are defined by their origin  $i$ , their final destination  $j$  in  $N$ , the container transport demand  $d^o$ , the container's availability time  $\tau_d^o$  and finally the container's arrival time  $\tau_a^o$  of order  $o$ . When an order is transported from its origin to its destination by a set of services in  $S$ , applies that  $o^u \circ o^s \circ o^k$ , i.e. that the service  $u$  transporting the order  $o$  succeeds the service  $s$  and the service  $s$  succeeds the service  $k$  transporting all the same order  $o$ .

In order to tract all order assignments within a set of services, an operator is created. The set of feasible services transporting containers from origin  $i$  to destination  $j$  at departure time  $t_d^s$  and arrival time  $t_a^s$  is defined as  $\delta^s(i, j, m, R, t_d^s, t_a^s) = \{s \in S \mid i \in N \text{ and } j \in N\}$ .

The model's objective is to minimize the objective function  $P$  defined in equation 4.1. The first summation represents the transport costs generated, while transporting customers' orders through the network services, while the second summation calculates the transfer costs. The third and fourth summation denote the environmental impact, separated in transport and transfer effect. In order to adapt the importance of the environmental impact, the weight factor  $w_e$  is created. Furthermore,  $w_e$  enables the

conversion of the environmental impact (measured in kg  $CO_2$ -eq.) to a monetary impact, measured in Euro.

$$P = \sum_{o \in O} \sum_{s \in S} X^{so} \cdot C^s + \sum_{j \in N} \cdot n_j \cdot T_c + w_e \left( \sum_{o \in O} \sum_{s \in S} X^{so} \cdot E^s + \sum_{j \in N} \cdot n_j \cdot T_e \right) \quad (4.1)$$

The objective function is subject to some constrains, necessary for modeling transport processes and the different transport planning scenarios. The constrain taking care for the container flow in the transport network is presented in 4.2, ensuring that everything that goes in must go out again and is equal to the demand of containers of order  $o \in O$ .

$$\sum_{s \in S | i=n} (X^{so}) = \sum_{s \in S | j=n} (X^{so}) = d^o \quad \forall o \in O, n \in N \setminus \{\text{origin } o, \text{ final destination } o\} \quad (4.2)$$

In order to create a capacitated network, it must be ensure that the services' capacities are not exceeded at any time and that all orders start and end at their respective origin and destination. Therefore the sum of all orders transported by a service (at a given time) must be less than the total services' capacities (see Equation 4.3). If a use case with flexible services' capacities is selected than Equation 4.3 is substituted by 4.4.

$$\sum_{o \in O} X^{so} \leq q_p^s \quad \forall s \in S \quad (4.3)$$

$$\sum_{o \in O} X^{so} \leq q_f^s \quad \forall s \in S \quad (4.4)$$

The correct time sequencing of selected services (time integrity) must be guaranteed for the shortest possible calculated transport route (also named path, i.e. a composition of a consecutively execution of services) using the network services. Thus, the path integrity, in terms of time, for order  $o \in O$  has to be proofed. Equations 4.5, 4.6, 4.7 and 4.8 present the mathematical description, for the four possible cases. Since truck services are always available in terms of time, cases i) and ii) comply with the path integrity. Case iii) addresses the sequence condition of scheduled base transport services. Finally case iv) ensures that a truck service arrives on time for the succeeding transport service.

$$i) \quad \text{if } m^s = m^u = \text{truck} \quad \text{than path integrity is true} \quad (4.5)$$

$$ii) \text{ if } m^s = \text{train or barge, } m^u = \text{truck} \text{ then path integrity is true} \quad (4.6)$$

$$iii) \text{ if } m^s = m^u = \text{train or barge, } t_a^s + T_t \leq t_d^u \quad \forall s, u \in \delta(s \in S) \quad (4.7)$$

$$iv) \text{ if } m^s = \text{truck } m^u = \text{train or barge, } t_d^s + R^s + T_t \leq t_d^u \quad \forall s, u \in \delta(s \in S) \quad (4.8)$$

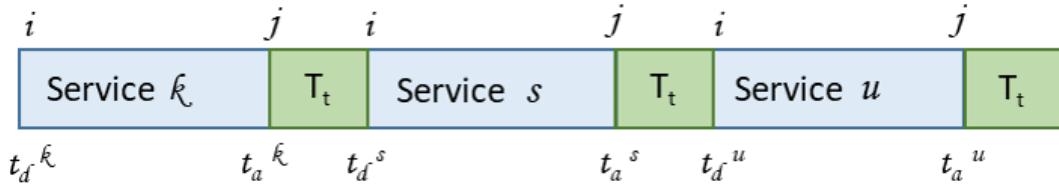


FIGURE 4.2: Graphical representation of services time sequencing and transshipment time

Once the time integrity of possible combinations of services is given, the in time delivery of all orders must be checked. Equation 4.9 present the mathematical description of the constraint to which the objective function is subjected, ensuring an in time delivery of an order. For a service in feasible path combinations (time integrity true) applies the Equation 4.9.

$$\tau_d^o \leq t_d^s \leq t_a^s + T_t \leq t_d^u \leq \tau_a^o \quad \forall s \in S, o \in O \quad (4.9)$$

If a use case with flexible time of arrival for an order  $o$  is selected than  $\tau_a^o$  will be substituted by  $\tau_f^o$  as seen in Equation 4.10. In both equations, 4.9 and 4.10, when  $s$  represents the last service, i.e. the service destination,  $j$ , is equal to the final destination of  $o$  then the condition regarding  $\leq t_d^u$  is erased.

$$\tau_d^o \leq t_d^s \leq t_a^s + T_t \leq t_d^u \leq \tau_f^o \quad \forall s \in S, o \in O \quad (4.10)$$

A maximum number of transshipments per transport order is set for minimizing the computational effort (see Equation 4.11). This parameter can be changed depending on the network size.

$$T^o \leq T^{max} \quad \forall o \in O \quad (4.11)$$

This mathematical model will be the basis for calculating the minimum global network costs for all orders  $O$  being transported to their final destination through the network of multimodal services. Thereby, the route with the minimum cost for an order will be calculated, so that the optimal services to be used will be selected. In chapter 5 the different applied optimization procedures will be explained, where the objective function (Equation 4.1) will be used as fitness function for evaluating the monetary costs generated by an order as well as for the global network.

## 4.2 Model architecture and modules

The model is created for supporting tactical and operational synchromodal transport decisions, like simulating the transport flow and cargo routing, supporting orders' assignment decisions or creating optimal schedules for transport services and their capacities. Therefore this quantitative model enables the simulation of inter-dependencies of transport factors and offers the flexibility to adapt to different transport scenarios. Within the different modules present below the user will have the possibility of setting different network and impact parameters.

Figure 4.3 presents a pictogram of the model's architecture. The picture presents the different modules of the model, an overview of the data flow and the different modules' interactions. The architecture is designed considering its scalability and is composed by the following modules [Fen18]:

1. Data enrichment and pre-processing: This module cares for the correct enrichment of the transport network and shipping customers data, i.e. orders. The goal is to enable an automatic reading, pre-processing and integration of all needed data for the model. The data from the transport network is characterized by the information regarding transport services and infrastructure characteristics. Some of this characteristic are constant in time e.g. location, connections or route distances, while other network data is variable over time (time dependent), like planned schedules or service's capacity. The shipping customer data is characterized by the transport service searched, which comprises the information about

origin, destination, cargo specifications and time constrains. The cargo specification like number of containers, weigh, volume or refrigeration option, influence strongly the results of environmental and costs assessment. A detailed overview of the needed data for the model will be presented in [section 4.3](#).

2. Network implementation and modeling: This module creates the transport network as a multi-directional graph. The network is modeled with nodes representing transport terminals, cargo sources and sinks and with multiple edges representing the different transport services with their corresponding modes. A detailed explanation of the network creation is also given in the following [section 4.3](#).
3. Transportation impact assessment: The impact assessment module calculates the monetary costs and the environmental impact generated for transporting customers shipments. The model uses fixed and variable parameters fetched within the first step. The modeling of monetary costs and environmental impact are explained in more detail in [section 4.4](#) and [section 4.5](#) respectively.
4. Optimization algorithm: This module interacts with the network module and the impact module within the whole optimization process for getting the best route and services selection. Obtaining the information from the preceding modules, following information will be the input for the chosen algorithm: (1) costs, (2) environmental impact, (3) transport duration and time schedules and (4) transport capacity. The optimization strategy can vary and can be adapted depending on the use case to be evaluated. The different optimization approaches will be in detailed presented in [chapter 5](#).
5. Post-processing and user interface (UI): This module is created for easily setting important parameters within the various optimization strategies, simulating and evaluating different scenarios as well as visualizing the results.

The focus of this work is set on the three marked modules: network representation, optimization algorithm including different strategies and the evaluation of the impact assessment in terms of costs and environmental impact. The presented model enables the analysis of multimodal freight transport networks and has been implemented in Python 3.6.

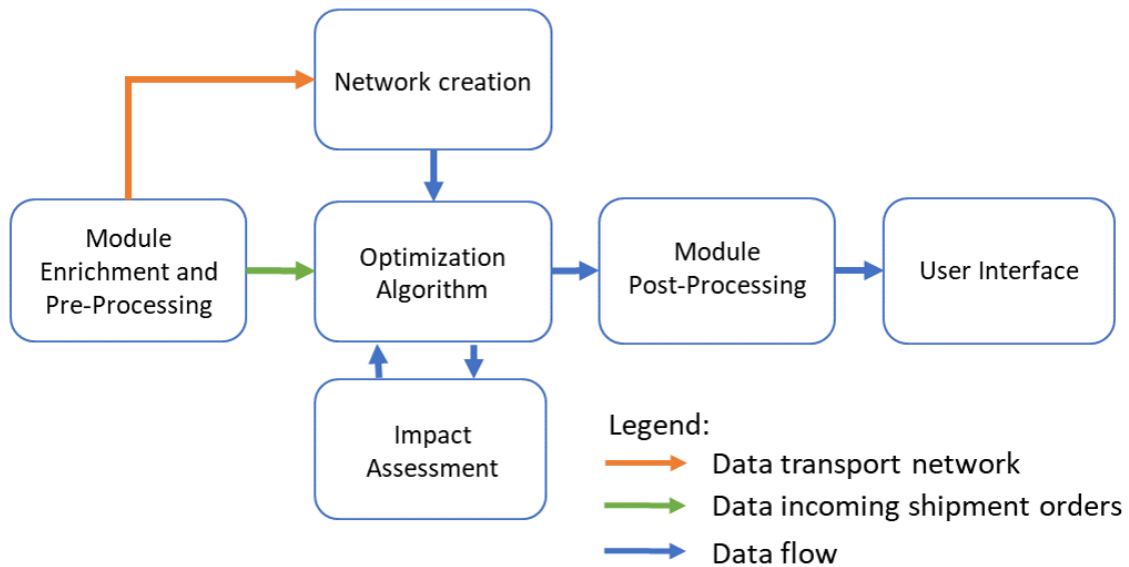


FIGURE 4.3: Model architecture

### 4.3 Modeling transport network and services

As presented within the synchromodal problem description (section 4.1), a transport network is denoted by the given transport services, connecting origins, destinations and transshipment points, i.e intermodal terminals. Table 4.3 lists the data needed for representing the transport network. Based on this data, the transport network provides later on the environment to simulate the different scenarios to be investigated. The table presents in three columns the features of each database: the in-coming customer shipments (named from now on transport orders), the freight transport services and the network information. The intermodal network contains truck, train and barge services. Underlined features are calculated using the impact module.

As stated before, the network will be represented as a multi-directional graph in which the nodes represent origin and destinations of listed transport services and orders, while the edges represent all different transport services between the nodes. Traditional graphs used for describing transport network consider one connection between nodes. Since a few years however, the networks are represented with multiple arcs [ACC09], thus more than one connection between nodes is possible.

Each service is characterized by its schedule, capacity of free container slots, transport mode and vehicle type. The information about the vehicle type being used is needed for the specification of the environmental impact and costs produce by the service, e.g considering the differences between diesel or electric trains. It should be noted that the duration and distances of transport services are static variables, following the

TABLE 4.3: Data needed

Orders	Services	Network
<ul style="list-style-type: none"> <li>• Origin terminal</li> <li>• Destination terminal</li> <li>• Number of containers (TEU)</li> <li>• Weight (tonnes)</li> <li>• Time availability</li> <li>• Time to deliver</li> <li>• Time to deliver (flexibility)</li> <li>• Distance</li> </ul>	<ul style="list-style-type: none"> <li>• Terminal start</li> <li>• Terminal end</li> <li>• Transport mode</li> <li>• Distance</li> <li>• Available capacity (TEU)</li> <li>• Capacity flexibility (TEU)</li> <li>• Start time</li> <li>• End time</li> <li>• <u>Costs</u></li> <li>• <u>Environmental</u></li> <li>• <u>Transshipment costs</u></li> <li>• <u>Transshipment environmental impact</u></li> </ul>	<ul style="list-style-type: none"> <li>• Start terminal</li> <li>• End terminal</li> <li>• Energy truck</li> <li>• Energy train</li> <li>• Energy barge</li> <li>• Factor C02 truck</li> <li>• Factor C02 train</li> <li>• Factor C02 barge</li> </ul>

schedules for barge and train services, while an average transport velocity for truck services (see assumption 5 in [subsection 4.1.2](#)) is given. They can be updated every time, as changes occur.

Similar to the transport services, transshipment points are characterized by their location, duration, costs and environmental impact per container. In the following [section 4.4](#) and [section 4.5](#) the assessment of costs and environmental impact of transportation, including transshipment services, is presented in detail. The values are considered static for the optimization problem, but within the costs calculation time dependent variables, like terminal utilization or service capacity, are taken into account.

## 4.4 Modeling intermodal transport costs

Intermodal transport is denoted by multi-modal transport services with usually three transport legs: pre-carriage, main transport and post-carriage. Within pre-carriage the cargo is usually transported by road to the start terminal to continue its main

route by ship or train to a terminal near to the final destination. Post carriage to the final customer happens in most of the cases by truck.

As described in [chapter 2](#) operational processes in intermodal transport involve a large number of actors, the execution is often different as planned, lot of services are done through subcontractors and the large majority of logistic services are payed based on contracts stipulated for a fixed period of time between the parties. These characteristics entail that transport costs are very difficult to comprehend, to calculate and to generalize.

As seen in [Table 3.3](#), in literature the topic of modeling intermodal transport costs is often simplified to handling costs per container and transport service. The transport costs are often considered as given and not further investigated. The few detailed cost models for combined transport described in the recent literature are characterized by a complex parametrization.

Six costs transport models, following a process-oriented bottom-up approach, are discussed in this section. This approach enables the calculation of sub-processes, where the total costs are calculated as the sum of the costs of the partial process. The advantage of this holistic bottom-up approach to the costing model is the transparency of how the costs are composed. On this basis, an evaluation of the relevance of certain cost items is possible. Besides, the model can be easily adapted to new transport situations and new players.

The six exemplary cost models selected to represent the current state of research are listed below:

- The model from Schwarz [[Sch06](#)] is characterized by a precise representation of the cost matrix for multimodal transport with a focus on seaport hinterland traffic. However, the required data can only be determined for specific routes due to the large detailed knowledge for each costs' structure. The provision of the necessary data for the European economic area is currently not feasible. The use of the cost model for practical applications is therefore only possible in a highly transparent transport network.
- The costs model developed by Eiband (see [[A. 14](#)] and [[Eib14](#)]) exclusively considers road and rail combined transport. The costs of rail transportation is divided in detail into the individual cost units and factors. The comparison with the pure road transport is very rudimentary, since only high aggregated values are used for road transport.

- The Wiegmans and Konings [WK13] model only handles the combined traffic road - waterway. For this aspect, the individual cost factors are presented in detail. The cost model also allows flexible adaptation to changing conditions in the economic environment. Wiegmans and Konings try to understand the advantage in competitiveness of intermodal inland waterway transport over pure road transport. For this purpose, they developed cost models for both transport methods, each of which depicts all cost units involved and divided into variable and fixed costs.
- The RECORDIT costs model [Bla03] was developed in the EU project also named RECORDIT and pursues a comprehensive approach, taking into account internal and external costs. It has served as an important reference in numerous scientific publications. The crucial difference to other models lies in the detailed consideration of external costs, e.g. the impact of transport in air pollution, accidents, noise pollution, health or global warming. The developed DSS enables the analysis of different transport scenarios and routes.
- The model from Janic et al. [Jan07] is based on the findings of the RECORDIT project. However for the external costs it uses only the aggregated values from the RECORDIT model.

#### 4.4.1 Requirements for the transport costs modeling

The development of the costs model addresses the simulation of real transport costs in order to support entrepreneurial decisions of transport companies. The intermodal costs model is created with the goal of calculating real generated transport costs and comparing the transport costs depending on a new routing choices. Therefore, the model is designed to allow the calculation of comparable cost values for any type of transport routes and transport volumes in Europe.

The requirements for the model are defined as follows:

- Modeling of multimodal transport: The model will cover road, rail as well as inland waterway transport. The focus is set in hinterland ground transportation. Air transport will not be considered since this transport mode is usually used for specific cargo or in special and hurry situations. Besides, it represents a transport with high environmental impact [Eur16] so that its utilization should be minimized as far as possible. Overseas shipping has a strong influence in the amount and timely distribution of cargo within the hinterland [Tav+11] [HT17]. Thus is an important aspect for analyzing the transport demand and

its distribution, but it does not play an important role, when deciding on the hinterland transport route.

- Generalized model: The cost model should allow the calculation of any European transport routes, i.e. it has to consider the different costs structures between the countries [Eco+15].
- Bottom-up approach: The comparison of the different transport scenarios in intermodal transport requires maximum transparency of the underlying cost units. The transparency and comprehensibility of costs and the willing to adapt the model to a wide range of transport situations, requires the development of a model with a bottom-up approach.

#### 4.4.2 Costs structures and modules

The intermodal transport costs model developed in this work includes four different calculation modules for (1) road transport, (2) rail transport, (3) waterway transport and (4) transshipments used for reflecting the originated costs in each transport mode and terminal services. Warehousing costs, as a part of usual logistic processes, are not considered, since the focus of the model remains the comparison of transport route's choice, when promoting a better modal split within intermodal transport and warehousing cost can be considered as independent of the route's choice.

Table 4.4 lists the relevant internal costs for operation and the variables considered in each module. Underlined factors are country dependent, so that each cross-border transport route has different costs, while variables marked with asterisk (\*) are time dependent.

#### 4.4.3 Mathematical description of costs model

In this section the mathematical description and formulas used for calculating generalized intermodal transport costs in the European transport network are presented. This modeling approach has been presented in a very summarized form in [Fen18]. In this section the modeling approach will be presented in more detail. The model developed in this work uses the costs structure presented in Table 4.4. Table 4.5 presents the variables and parameters used.

The total costs  $C_G$  will be determined, following Equation 4.12, as a summation of the costs generated by each transport mode and the transshipment processes.

TABLE 4.4: Operational internal costs for each mode

Road transport	Rail transport	Waterway transport	Transshipment
<ul style="list-style-type: none"> <li>• Equipment (procurement and amortization)</li> <li>• Maintenance (including tire costs) and repair</li> <li>• <u>Fuel*</u> and lubricant</li> <li>• <u>Toll</u></li> <li>• <u>Personnel</u></li> <li>• Tax and insurance</li> <li>• Overhead and margin</li> </ul>	<ul style="list-style-type: none"> <li>• Equipment rent</li> <li>• <u>Energy</u></li> <li>• Shunting</li> <li>• <u>Train path charge</u></li> <li>• <u>Personnel</u></li> <li>• Overhead and margin</li> </ul>	<ul style="list-style-type: none"> <li>• Equipment rent</li> <li>• <u>Harbor dues</u></li> <li>• <u>Fuel*</u></li> <li>• <u>Personnel</u></li> <li>• Overhead and profit</li> </ul>	<ul style="list-style-type: none"> <li>• Equipment (procurement and amortization)</li> <li>• <u>Energy costs</u></li> <li>• Overhead and profit</li> </ul>

TABLE 4.5: Variables for modeling transport costs [Fen18]

Variables	Description
$x$	Number of containers per customer's shipment measured in TEU, total weight (t) or volume (m <sup>3</sup> )
$d$	Distance from origin to destination (km)
$C$	Total costs (Euro)
$H$	Handling costs (Euro/container)
$\alpha$	Overhead (%)
$\beta, \gamma$	Margin of road transport and rail transport respectively (%)
$\varepsilon$	Share of average empty wagons (%)
$\delta$	Proportion of distance of each country (%)

$$C_S = \sum C_{Road} + \sum C_{Rail} + \sum C_{Waterway} + \sum C_{Transshipment} \quad (4.12)$$

### Road transport costs

The road costs are calculated following the approach from [Wit14], where the road transport costs are divided in ten different type of costs as presented in Table 4.4. Equation 4.13 calculates the total costs generated by road transportation.

$$C_{Road} = ((C_{Op-Road} + C_{Personal} \cdot f_{Personal} + C_{Fuel} \cdot f_{Fuel}) \cdot (1 + \alpha) \cdot (1 + \beta)) \cdot x \cdot d_{Road} \quad (4.13)$$

Where the operational costs,  $C_{Op-Road}$  are defined as follows:

$$C_{Op-Road} = Maintenance + \frac{Taxes + Insurance + Depreciation + Interest}{Milage} \quad (4.14)$$

Appendix A, Figure A.2 presents an overview of the costs units and the exemplary values taken into account. More details about the calculation of costs and the exemplary values taken into account, can be found in [Lar15]. The terms used in both equations for road transport are defined as follow:

- Personal costs,  $C_{Personal}$ : Although personnel costs are fixed costs, they vary greatly from country to country. The personnel costs include driver's wages, expenses and employer's social security contributions.
- Fuel costs,  $C_{Fuel}$ :
- Operational costs:
  - Equipment: costs of procurement and amortization
  - Maintenance: This cost unit includes both variable and fixed portions of costs and is taken into account by hauliers as a kilometer-based flat rate.
- Toll: this cost is generated by the transport of goods using highways with fees. They are country as well as route dependent.
- Taxes and insurance: these are country dependent fixed costs for LSPs
- Overhead and margin: The profit margin and any other overhead costs are taken into account over an averaged percentage.

In order to map and calculate the differences between countries and daily fuel changes, a country dependent fuel factor  $f_{Fuel}$ , variable on a daily base and a country dependent personal factor  $f_{Personal}$  are determined. The model takes as reference the labor and fuel costs in Germany. Through the personal factor, the labor costs are converted to the specific country. The values for personal factor can be found in Appendix A Figure A.1 [Eur18].

### Rail transport costs

Rail transport costs are calculated based on the costs models of [A. 14], [Eib14]. Equations 4.15, 4.16, 4.17 and 4.18 present the mathematical formulation of the different costs units for rail transport.

$$C_{Rail} = (C_{Rail-internal} + C_{Route}) \cdot x \quad (4.15)$$

The internal rail costs (calculated per number of container) are structured similar as road costs (Equation 4.13), considering also the same factors for adapting fuel and personal costs to country and daily changes.

$$C_{Rail-internal} = ((C_{Op-Rail} + C_{Personal} \cdot f_{Personal}) \cdot (1 + \gamma)) \cdot x_{wagon} \cdot (1 - \varepsilon) \cdot d_{Rail} \quad (4.16)$$

$$C_{Op-Rail} = \left( \frac{Equipment + Shunting}{d_{Rail}} + Energy \right) \cdot (1 + \alpha) \quad (4.17)$$

The shunting costs incur in the handling areas of rail terminals and will be charged by the terminal operator. They are taken into account with fixed costs of €150 per train [Eib14].

Equation 4.18 calculates toll costs of a rail route, the so-called train path price,  $C_{Path}$ . The train path price have to be payed for the use of train tracks and vary greatly from country to country. Besides the country dependency and the route's length, the path price can even vary within a country depending on the used railway or on the gross weight of the hauled load. Appendix A Figure A.4 shows the results of a statistical study of train path prices in Europe. This cost covers a large range from €10 per train in Latvia to €0 per train in Norway, where access to the rail network is free [Eura].

$$C_{Route} = \sum_{country} C_{Path}(country) \cdot \delta_{country} \cdot d_{Rail} \quad (4.18)$$

Furthermore, the energy costs depend on the consumption and the electricity price. The consumption depends on various factors like train weight, speed, route profile or type of locomotive. The consumption is assumed to be 0.018 kWh/tkm [Sch06], whereas the train weight is based on the weight of the locomotive, the weight of 30 wagons and the weight of an average load. The electricity price for industry is taken from [Sta18]. Since train companies return considerable amounts of electricity to the grid by recuperation during braking, they have around 5% higher discounts than other major industrial consumers [Eib14].

Appendix A, Figure A.3 presents an overview of the costs units and the exemplary values taken into account for rail costs.

### Waterway transport costs

Waterway transportation costs are based on [Sch06]. Their mathematical formulation is presented in equations 4.19 and 4.20. Similar to road and train costs units, a country dependant personal factor is considered.

$$C_{Waterway} = C_{Op-Waterway} \cdot f_{Personal} \cdot x \cdot d_{Waterway} \quad (4.19)$$

Waterway costs are calculated in a more generalized way as an average of annual performance, i.e. related to the amount of containers transported and annual mileage. Thus, the operational waterway costs are simplified to the sum of fix and variable costs.

$$C_{Op-Waterway} = \frac{\sum Fixcosts + \sum Variablecosts}{D_{annual} + C_{barge}} \quad (4.20)$$

Where  $D_{annual}$  represents the annual total distance traveled and  $C_{barge}$  the total container capacity of the barge. Appendix A, Figure A.5 presents an overview of the costs units and the exemplary values taken into account for waterway costs.

### Transshipment costs

The transshipment costs are calculated using equation 4.21, where  $H$  varies depending on the type of terminal, i.e. train or ship terminal.

$$C_{Transshipment} = H \cdot x \quad (4.21)$$

The costs of handling containers in inland waterway shipping are heavily dependent on the port terminals size, equipment, location and utilization. While the fee per cargo handled varies greatly from port to port, the price is also influenced by terminals size. Big terminals have extensive equipment to be able to deal with a larger number of ships at the same time, which increase the total handling costs [Lar15]. The prices quoted by market participants have a wide range and varied for example in the year 2000 from €24 to €112 per transshipment [Kru00]. This difference also results from different subsidization measures given by the individual states. For example, up to 85% of investment in Germany, up to 25% of investment in the Netherlands and up to 80% of investment in Belgium are granted or taken over by the state [WK15].

The last major impact on the costs of transshipment processes is the terminal's utilization as most of the terminal cost is caused by fixed costs. The figures presented by Wiegman and Konings are used in this work, where a distinction between five terminal types according to their annual performance of handled containers is given [WK15]. The values range from €100 to €60 in small terminal and from €40 to €20 in large terminals depending on the terminal utilization.

Regarding train terminals, an inquiry to a terminal operators of large number of terminals in Germany, confirms the costs structure specified above and provides a flat-rate cost value with a bandwidth of €19 to 25 per loading unit for the entire process [Lar15]. This cost interval is confirmed by experts of transport companies and by the given values of €17,5 to €25 in [A. 14] and €20 to 30 in [Sch06]. In this work, an average base rate of €20 per loading unit for a transshipment in a railway terminal is used.

## 4.5 Modeling environmental impact

Similar to the modeling of transport costs, the modeling and evaluation of the environmental impact of transport processes can be performed in many forms and grades of detail. However, the Life Cycle Assessment (LCA) methodology is a well-known standardized method applied to evaluate the environmental impact of products, processes and materials in a systematic and objective form [DINly]. Therefore, the mathematical model used for measuring the environmental impact of transportation is based in this work on the methodology of LCA.

The LCA approach is commonly used to compare the overall environmental burdens from different competing technologies. Besides, this method has already been used for the environmental impact assessment in different transport situations, for example in transport operations [M.J13] or for the comparison of different transport routes in wood transport [GG+09]. This approach for measuring the environmental impact of different transport vehicles and routes has been implemented and presented in [Fen15] for the assessment of the environmental performance of the new intermodal loading units presented in [subsection 2.2.3](#).

An LCA approach is structured and comprises always following four phases: the definition of the goal and scope of the work, an inventory analysis including the gathering of needed data, the calculation of the impact assessment and finally an interpretation and discussion of results with an improvement analysis [Int97].

### 4.5.1 Goal and methodology

The goal of LCA in this work is to measure and model the environmental impact of different generated intermodal transport routes including the operational transport environmental costs and infrastructure's energy usage. The functional unit taken as a reference for inputs and outputs is defined in this study as a container unit of cargo transported from its origin to destination for a given route.

Focus of the environmental impact assessment is the phase of operation during the life cycle of the different transport products. Until very recently, shippers decided in favor of a specific way of transport only based on price. Fortunately within the last years, the ecological impacts is considered more important in the decision making process. As discussed in [chapter 2](#) the discussion about the  $CO_2$  foot print promotes the usage of a monetary charge dependent on the environmental impact measured in kg  $CO_2$ -Equivalent [Pub16].

### 4.5.2 Inventory analysis

The inventory analysis and environmental loads for all elements have been determined using the database Ecoinvent V2.2, which uses data from Europe (code RER) and Switzerland (code CH). Within this database the inventory processes and loads used for the analysis of transport processes are the transport process measured in tkm. These transport loads represent a generalized factor for each mode that includes three types of loads: The processes for vehicle (production, maintenance and disposal), vehicle operation and the use of the infrastructure (construction, operation and disposal) [M.

07]. These loads for the transport data are calculated via an averaged loading value to take also empty runs into account. Table 4.6 presents the processes selected for the inventory analysis and the corresponding values of each factor.

TABLE 4.6: Processes for the inventory analysis extended from [Fen15]

Process	Area- Code	Unit	GWP fac- tor (kg $CO_2$ -Eq)	ODP fac- tor (kg CFC-11- Eq)	LU factor ( $m^2a$ )
transport, lorry 40t, full	CH	tkm	1,6639	2,4504E-08	0,022166
transport, freight rail	RER	tkm	0,039562	2,5996E-09	0,0019368
transport, barge	RER	tkm	0,045878	4,345E-09	0,0027783
electricity, high voltage, production specific country, at grid	DE	kWh	1,1364	6,8646E-09	0,028337

In order to calculate the environmental impact of a transshipment process, the amount of energy needed in these processes has to be estimated. The energy required to handle the different types of containers is assumed to be the same since the procedure is very similar. The energy required for the transshipment process is calculated with the Well-to-Wheel (WTW) concept in equation 4.22.

$$WTW = Well - to - Tank(WTT) + Tank - to - Wheel(TTW)(inKWh) \quad (4.22)$$

The energy used by handling a container in a rail cargo transport center is estimated by [KIS02] with 4.4 kWh/TEU (TTW) plus transfer process (WTT). We assume that this value is the same for waterway terminals. The value of WTT depends on country and has been gathered using the information provided by the online-tool EcoTransIT World [KIÖ11]. This approach has been also used e.g. in [Dem+15].

### 4.5.3 Impact assessment

In this work the CML method can be applied to a large set of impact categories [S. 12]. For the case of measuring transportation impact, following three impact categories

have been selected: Global Warming Potential (GWP) measured in kg CO<sub>2</sub>-Eq, Ozone Depletion Potential (ODP) measured in kg CFC-11-Eq and Land Use (LU) measured in  $m^2a$ . [Table 4.7](#) describe the impact categories measured within the inventory analysis. These categories are selected as being widely used in published LCA studies ([\[Cam\]](#), [\[GG+09\]](#), [\[M.J13\]](#) and [\[MS16\]](#)) and due to the relevance of the environmental impact in transport system.

TABLE 4.7: Inventory analysis using the Ecocat CML 2001 [\[Fen15\]](#)

Impact category name	Ecosubcat	Unit	Description
Global warming potential (GWP 100a)	Climate change	kg CO <sub>2</sub> -Eq	This category aggregates all relevant emissions of substances, like CO <sub>2</sub> , CH <sub>4</sub> or N <sub>2</sub> O that increased the global warming effect.
Stratospheric ozone depletion (ODP 25a)	Stratospheric ozone depletion	kg CFC-11-Eq	This category aggregates all relevant substances that deplete the ozone stratospheric layer.
Land use (LU)	Land use	m <sup>2</sup> a	This value, also named occupation impact, represents the land that potentially disappears measured in square metre of land per year, $m_2a$ .

The total environmental impact  $E^S$  will be determined, following [Equation 4.23](#), as a summation of the generated environmental impact by each transport mode and the transshipment processes.

$$E^S = \sum E_{Road} + \sum E_{Rail} + \sum E_{Waterway} + \sum E_{Transshipment} \quad (4.23)$$

Exemplary presented for measuring the impact assessment of road transport for GWP impact category,  $E_{Road}$  is calculated following the [Equation 4.24](#)

$$E_{Road} = E \cdot f_{GDP-Road} \cdot t \cdot d_{road} \quad (4.24)$$

where  $t$  denotes the container weight and  $d$  the transported distance by each mode.

## 4.6 Summary

Within this chapter the mathematical description of the objective function used in the sychromodal freight transport model, also named intermodal freight transport model with sychromodal services, is presented. The goal of the objective function is to minimized the transport costs and environmental impact generated by the transport of customers' orders within a multimodal transport network, represented by a number of transport services.

In [section 4.1](#) the model description, specifications and the mathematical description of the model including constrains, assumptions are presented. In order to evaluate the improvement of the assignment process, so that the best set of available services for each order can be selected, monetary and environmental costs are evaluated. Therefore in [section 4.4](#) and [section 4.5](#) the modeling of intermodal transport costs and environmental impact respectively is presented. These generalized costs and environmental impact model enables the comprehensibility and transparency of generated transport costs and are the basis for the fitness function evaluating the optimization improvement.

The model is created for supporting tactical and operational sychromodal transport decisions, like simulating the cargo distribution and shipment routing, supporting orders' assignment decisions or creating optimal schedules for transport services and their capacities. Therefore this quantitative model enables the simulation of interdependencies of transport factors and offers the flexibility to adapt to different transport scenarios. Within the next chapter different optimization approaches for an optimal routing and assignment of transport orders are discussed.

## Chapter 5

# Optimization of synchromodal transport planning

This chapter presents the implementation of three optimization model that were created in order to efficiently assign orders in a synchromodal network. [Figure 5.1](#) shows the general structure of [chapter 5](#). The chapter is build up by three blocks, each representing a different optimization approach. Two single objectives algorithms will be presented, starting from a classic optimization methodology in [section 5.1](#) to the generation of best orders' sequence using GA. The use of the algorithm NSGA-II for solving multi-objective problems in orders' assignments will be discussed. In all cases the output of the optimization model is an optimal assignment's sequence of orders, a plan of schedule and of service selection and the total monetary costs and environmental impact of the synchromodal network.

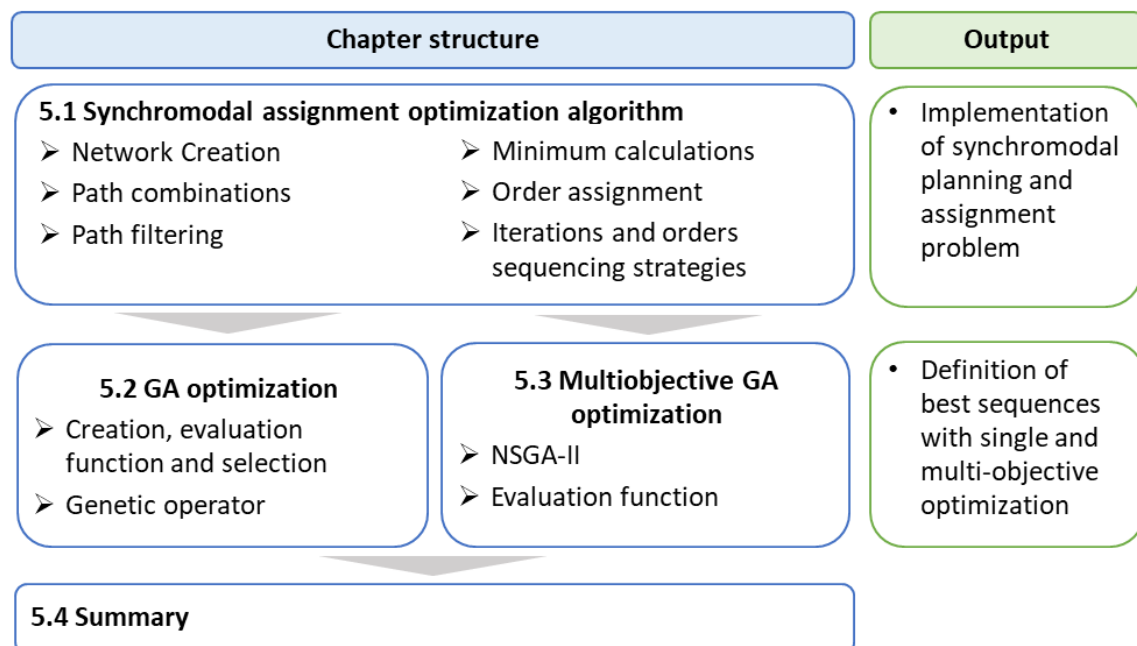


FIGURE 5.1: Chapter 5 structure and content flow

## 5.1 Synchromodal assignment optimization algorithm

In this section the most important methods and listings used for the calculation and simulation of the model will be presented, in addition to the logic behind the optimization model. The most important and relevant script for the algorithm can be found in Appendix B.

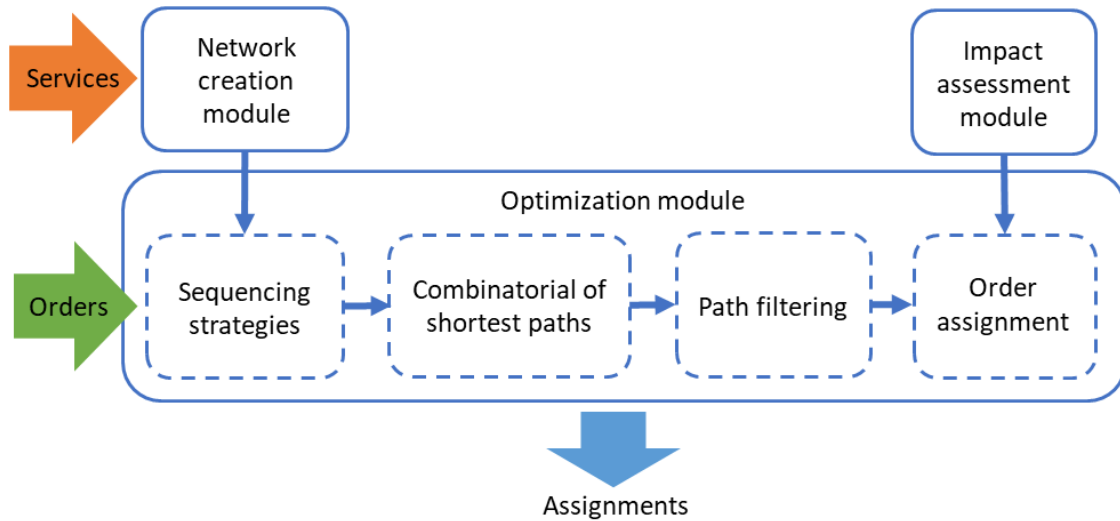


FIGURE 5.2: Steps of optimization algorithm

The optimization of the orders' assignment within a synchromodal network follows the overall concept presented in [Figure 5.2](#):

1. Network creation module: This module creates the network of cities using the data of services. The number  $N$  of shortest paths for each order are determined using the distances between nodes as a measure.
2. Within the optimization module following steps will be taken:
  - (a) Sequencing strategies: The optimization model follows a FIFO approach, thus the orders' sequence influences decisively the optimal assignment.
  - (b) All possible combinations of services that involve the cities along the shortest paths are gathered.
  - (c) All achieved combinations will be filtered on the following basis:
    - Path integrity: Within this step the feasibility in terms of time of the selected sequence of services will be checked. This means that the arrival of a service at the transshipment point must happen before the

- succeeding service leaves the node, including the needed transshipment time.
- In time delivery: Check if an order can be delivered in time.
  - Capacity availability: Check if the order TEUs are available along the path.
- (d) Assignment of orders: This step assigns an order to the route with the minimal cost and updates afterwards the capacity availability of the services.
3. Impact assessment module: This module interacts with the optimization module calculating the monetary costs and environmental impact of all filtered, i.e. feasible paths.

Figure 5.3 presents the main steps followed within the optimization module in an activity diagram. The implementation and description of the optimization steps are detailed in the following sections. The python libraries and packages used for the definition of the different methods and calculation steps are listed in Appendix Listings B.16 and B.17.

### 5.1.1 Network creation and path combination

For this work a python method named *createNetwork* was developed, which generates a transport network using the services' input data presented in chapter 4.3 Table 4.3. The corresponding code can be found in Listing B.1. This method creates a multi-directional graph in which the nodes are terminals of origin and/or of destination of the listed transport services, while the edges represent all different transport routes between the nodes. These edges contain all relevant information specified for each transport service e.g. origin, destination, mode of transport (road, rail or waterway) and the route distance.

The generated network will be used to spawn all possible shortest paths. These paths represent all possible transport routes between origin and destination and are defined by the booked service. In order to comply with the constrain on the maximum number of transshipments (see Equation 4.11) the cutoff parameter within the all simple paths method in python helps to set  $T^o$  by two. Furthermore, to reduce the computational time, the factor N is a setting parameter for limiting all possible paths to a maximum of N. Listing B.2 presents the method calculating N shortest paths.

In order to get all possible combination of edges, i.e. service combinations for a given path, a combinatorial method *intertool* is used (see B.3).

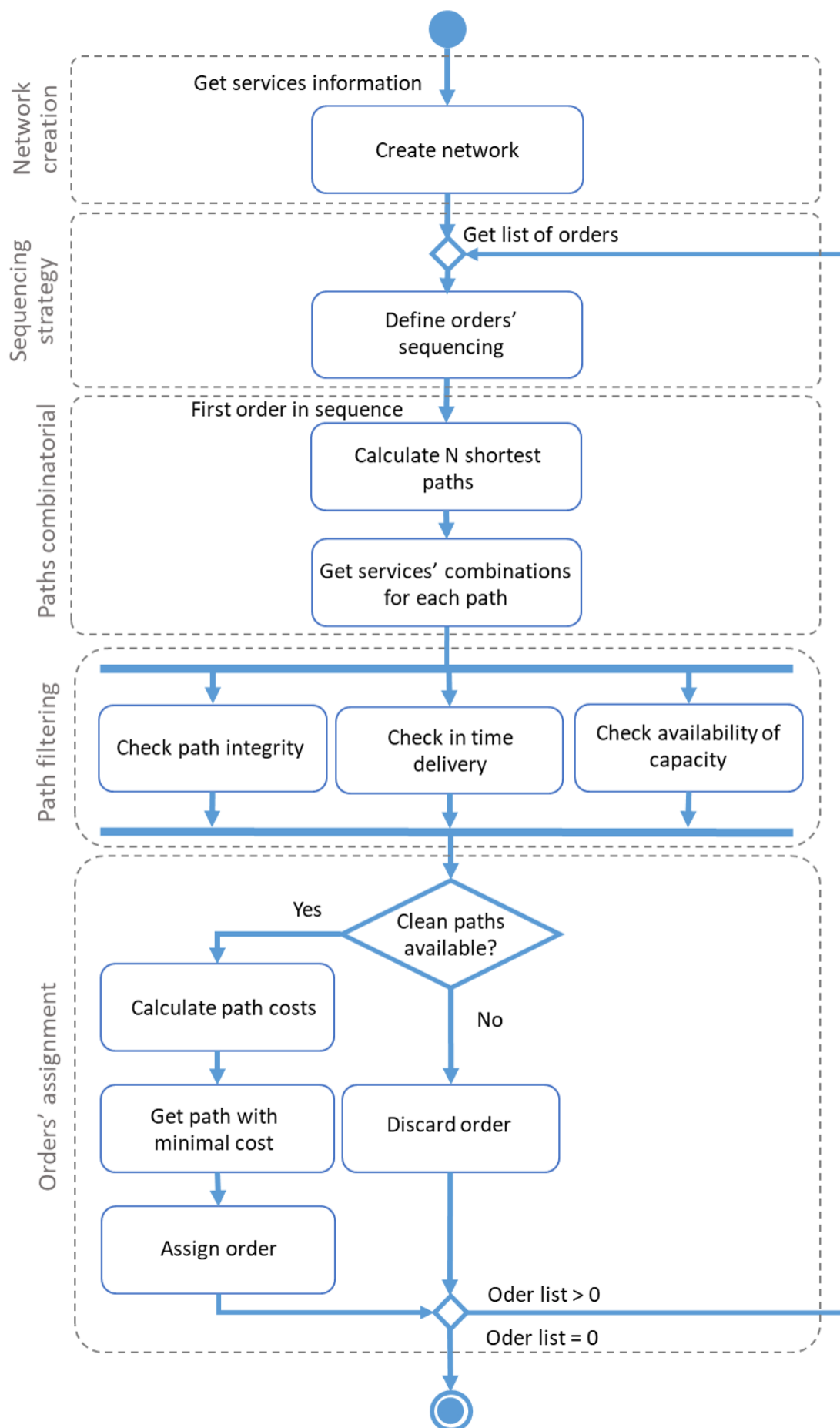


FIGURE 5.3: UML State diagramm for optimization algorithm

## 5.1.2 Path filtering

After all possible combination of paths are created, the fulfillment of all model constraints must be checked. This is done by the method *cleanPaths* (see Listing B.4), which guarantees that all services within a path will comply with the model constraints regarding service capacity, delivery time and the right connexion time between services, tanking into account transshipment time. The filtering occurs in a parallel way, returning only paths that satisfy all constraints.

The three methods used for filtering *checkPathIntegrity*, *timeDelivery* and *teuAvailability* are explained below.

### Path integrity

The method *checkPathIntegrity* ensures that the service sequence is feasible regarding time concerns as defined in equations 4.5 and 4.6. As described in chapter 4 and Figure 4.2 the model considers always a transshipment time between two services, regardless of whether a given cargo must be transshipped or not. A possible change of the cargo order in one service or the transshipment of other containers between two services are the reasons for ensuring always enough transshipment time between the arrival of the previous service and the departure of the next transport service, even if a given cargo is not moved.

Listing 5.1 presents the part of the model's implementation, where the time integrity of a route is checked for the transport modes train and barge, using the schedule of the selected services (Equation 4.5). For trucks only the duration of travel is considered, since truck services are always available by free capacity.

LISTING 5.1: Check path integrity method

```
def checkPathIntegrity(services_df,path):
    integrity=True
    arrival=0
    for i in range(len(path)):
        if services_df['mode'].loc[path[i]] in ['Train','Barge']:
            if services_df['start_time'].loc[path[i]].timestamp()>arrival:
                integrity &= True
                arrival=calculateServiceArrival(services_df,path[i],arrival)
            else:
                integrity &= False
```

```

else:
arrival=calculateServiceArrival(services_df,path[i],arrival)
logger.info('checkPathIntegrity'+str(path)+'->'+str(integrity))
return integrity

```

### In time delivery

The method presented in listing B.5 checks if an order can be delivered in the time given by the costumer, as defined in Equations 4.9 and 4.10. The selection of the flexibility option regarding order delivery time sets a new delivery time, which can be fixed by the costumer. By default an addition of 24 hours between availability and delivery will be considered.

### Capacity availability

The method presented in B.6 checks if each service along a certain path provides the required number of TEUs, as described in Equation 4.3.

The parallel filtering of all paths, proved by the three above described methods, delivers the set of feasible or clean paths for an order. This list of clean paths is the input for the last algorithm step, marked in Figure 5.3 order's assignment. Therefore two further methods are created in order to assign the given order to the best transport route (or path) including the assignment of transport service that will transport the cargo along the given route.

## 5.1.3 Order assignment

The main objective of the optimization problem is to decide on order's assignment, searching for the most beneficial cargo distribution for the whole transport network. Responsible for pursuing this objective is the method *assignOrder*, presented in Listing 5.2. It follows a FIFO approach, assigning an order to the best services, i.e. the route with minimum costs, considering in the mean time all network constraints. Further methods used in Listing 5.2 are attached in Appendix B.

LISTING 5.2: Order assignment method

```

def assignOrder(services_graph,services_df,orders_df,order_index,
    ↪ assignments,eurPerKg,stress_road,flexibility,teu_flexibility):
logger.info('Order'+str(order_index))
if not nx.has_path(services_graph,orders_df['start'].loc[order_index],
    ↪ orders_df['end'].loc[order_index]):

```

```

raise ValueError('This order cannot be distributed over the network.
↳ There is no path between the cities')
shortest_paths = get_N_ShortestPaths(services_graph,orders_df['start'
↳ ].loc[order_index],orders_df['end'].loc[order_index],3,3)
path_combinations=[getAllEdgesCombinations(getEdgesIndexes(
↳ services_graph,path)) for path in shortest_paths]
path_combinations = list(itertools.chain.from_iterable(
↳ path_combinations))
clean_paths = cleanPaths(services_df,path_combinations,orders_df,
↳ order_index,stress_road,flexibility,teu_flexibility)
logger.info('Clean Paths'+str(clean_paths))
if clean_paths:
minimal_cost_path,minimal_cost=getMinimalCostPath(services_df,
↳ clean_paths,orders_df['teu'].loc[order_index],eurPerKg)
logger.info('Minimal Cost Path'+str(minimal_cost_path))
assignments[order_index] = {'assigned':True,'path':minimal_cost_path,'
↳ teu':orders_df['teu'].loc[order_index],'cost':minimal_cost}
updateServices(services_df,minimal_cost_path,orders_df,order_index,
↳ stress_road,teu_flexibility)
else:
assignments[order_index]={'assigned':False,'path':[],'cost':(orders_df
↳ ['teu'].loc[order_index]*orders_df['air_distance'].loc[
↳ order_index]*2*1.15,orders_df['tonnes'].loc[order_index]*
↳ orders_df['air_distance'].loc[order_index]*0.2*eurPerKg)}

```

#### 5.1.4 Orders dispatching and sequencing strategies

The second method, *dispatchOrders* (Listing 5.3), tries, together with the main script for running the model, to dispatch the received sequence of orders using the provided network services. This method is the starting point of the optimization model and requires the following information:

- Sequence strategy for orders enrichment: Following the FIFO approach orders can be presorted by departure or delivery time, number of container to be transported (capacity) or predefined customer priority.
- Services data frame: This data frame contains relevant service's information as described in [section 4.3](#).

- Orders data frame: This data frame contains relevant order's information (see [section 4.3](#)).
- Assignments: This data frame registers the output of each iteration.
- Selection of flexibility options:
  1. Unlimited service capacity is an option helping to figure out stress services for the given orders data frame, i.e. the transport service with the highest demand based on the orders.
  2. Flexibility in delivery time of orders can be taken into account. This option enables setting marked customer's orders with a flexible delivery time.
  3. The capacity flexibility of the offered transport services can be set.

LISTING 5.3: Main and method for dispatching orders

```
def dispatchOrders(sequence, services_df, orders_df, assignments,
    ↪ stress_road, flexibility, teu_flexibility):
SR = createNetwork(services_df)
for i in tqdm(sequence):
assignOrder(SR, services_df, orders_df, i, assignments, stress_road,
    ↪ flexibility, teu_flexibility)

##### Main #####
services_df = pd.read_excel('MyData.xlsx', sheetname='Services')
orders_df = pd.read_excel('MyData.xlsx', sheetname='Orders')
assignments = {}
sequence=getDefaultSequence(orders_df)
dispatchOrders(sequence, services_df, orders_df, assignments, False, False,
    ↪ False)
```

Within the main script the data frames to be used, containing service' and orders' information, are selected. The sequence strategy is defined and the *dispatchOrders* method is called. The output is the assignment of orders following a FIFO approach.

The concept above follows the sequence of orders in which these are listed (per default). A change in the assignment sequence may improve the efficiency, both in the number of TEU assigned as well as in the total costs. Therefore the model enables to sort the order's sequence. The developed user interface generates automatically following sequences:

- Random: customer arrival

- Departure time: customer's orders are sorted by descending departure time
- Arrival time: customer's orders are sorted by descending arrival time

The optimization algorithm presented in this section enables the selection of the best services combinations for an order at a given time, taking into account available services, but ignoring the subsequent services' demand. Thus the optimum will always be achieved, from a local perspective, only for one given transport order at specific given time.

## 5.2 Genetic algorithm optimization of synchronodal order assignment

Genetic algorithms (GA) belong to the evolutionary search techniques, which are characterized by the use of analogies of natural selection mechanisms and learning processes for simulating evolutionary processes with the help of computers [CL04]. Following the definition given by John R. Koza, pioneer in the use of genetic programming: "The genetic algorithm transforms a population of individual objects, each with an associated fitness value, into a new generation of the population using the Darwinian principle of reproduction and survival of the fittest and naturally occurring genetic operations such as crossover (recombination) and mutation" [Koz07].

The good performance of evolutionary algorithms is well-known in solving high dimensional problems with a high number of feasible solutions: "Genetic Algorithms are good at taking large, potentially huge search spaces and navigating them, looking for optimal combinations of things, solutions you might not otherwise find in a lifetime" Salvatore Mangano, May 1995 [CK08].

Evolutionary algorithms follow the generalized approach presented in Figure 5.4. Four main steps occur in every generation, a selection process of the best individuals within the population, reproduction, crossover and mutation of selected individuals and finally an evaluation for measuring the optimal individuals. This process enables the evolution of the population developing individuals that deliver in each iteration better results.

For solving the problem of optimizing the sequencing strategy and deliver a global optimal cargo distribution and the assignment of services, GA are chosen due to their capability to analyzed large solution spaces. As seen in chapter 3 Table 3.1 GA follows a meta-heuristic approach which are suitable for solving integer programming problems.

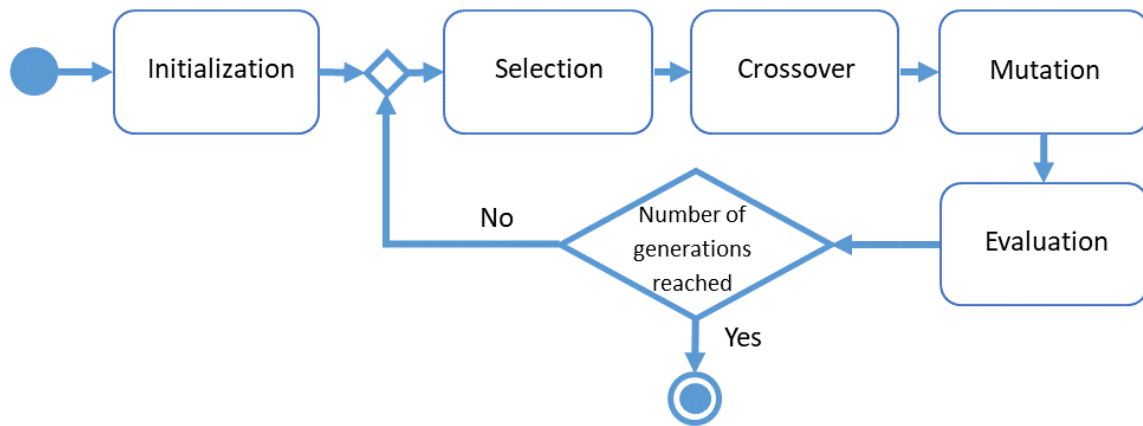


FIGURE 5.4: Main steps of a GA approach

Taking the above presented principles to the problem of synchromodal order assignment, following steps are required to optimize the sequencing of in-coming transport orders [NKC13]:

- Initialization: This step contains the creation of the first population. A population contains a constant number of individuals. Each individual is a different sequence of transport orders. This first population can be generated in a random manner or using smart generation methods.
- Evaluation: Every individual will be evaluated using a fitness function. This step provides the environment in which the individuals have to evolve.
- Selection: Those individuals getting the best results from the fitness function are adapting best to the desired environment. These individuals will be selected for mutation and reproduction.
- Reproduction: This step recombines, clones or mates the selected individuals with each other to generate a novel solution.
- Mutation: Some individuals are selected to undergo mutation and generate a new form of individual.
- Population replacement: The newly created individuals replace the old population of the solutions. This step is done at once for the orders sequences resulting in discrete generations.
- Termination: The loop repeating the creation of new generations finishes at the moment that a termination condition is fulfilled. Since the minimization of costs does not have an absolute minimum, the termination of genetic generation

occurs as soon as the maximum defined number of generations has been reached or when a certain number of iterations has passed without changing the result.

Within this single objective genetic optimization following constant factors are used to parameterize the problem:

- Number of orders ( $n_{orders}$ ): This number is given by the order's input data set.
- Population size ( $p_{size}$ ): This value varies depending on the number of orders. It needs to be large enough for guaranteeing an initialization of the problem rich and diverse in solutions.
- Number of parents ( $n_{parents}$ ): A constant for setting the number of individuals chosen for crossover and mutation.
- Number of mutations ( $n_{mutations}$ ): Parameter created for influencing the quantity of crossovers and mutations.
- Number of generations ( $n_{generations}$ ): Parameter which determines the termination of the optimization algorithm. This parameter is strongly dependent on the problem, i.e. orders size, available computational capacity and calculation time.

The Listing 5.4 presents the code implemented in python for the single genetic optimization of orders' sequencing. The most important methods used are listed in Appendix B.

LISTING 5.4: Main code implementation of GA

```

results={}
generation_counter = 0
population = generatePopulation(populationSize)
population_performance = calculatePopulationPerformance(population)
print('Generation_{}: Average Fitness={}'.format(generation_counter,
    ↪ evaluateGeneration(population_performance)))

while(generation_counter<nGenerations):
parents = selectParents(population,population_performance,nParents)
population=[]
bestParent = getBestParent(parents)
population.append(bestParent)
mutatedParents = mutateParents(parents,nMutations)### Factor nParents*
    ↪ nMutations
mutatedParents2 = mutateParents2(parents)### Factor 4*nParents
mutatedParents3 = mutateParents3(parents)### Factor 8*nParents

```

```

mutatedParents4 = mutateParents4(parents)### Factor 5*(nParents-1)
population = population+mutatedParents+mutatedParents2+mutatedParents3
    ↪ +mutatedParents4
population += generatePopulation(populationSize-len(population))
population_performance = calculatePopulationPerformance(population)
generation_counter+=1
print('Generation_{}: Average_Fitness={}'.format(generation_counter,
    ↪ evaluateGeneration(population_performance)))
results[generation_counter]={ 'bestParent':population[
    ↪ population_performance.index(min(population_performance))], 'cost
    ↪ ':min(population_performance)}

```

Within the next sections the implementation of the GA for single optimization is presented following the steps shown in [Figure 5.4](#). This algorithm will present three variants, depending on the chosen settings and genetic operators:

1. Random algorithm: this algorithm used specific genetic operators created for the considered problem of order assignment and sequencing strategy. The initialization procedure is random based.
2. Random smart generation algorithm: this algorithm uses the same genetic operators as the variant above but is formulated with an "already optimize" initialization procedure.
3. DEAP algorithm: this algorithm implement classical genetic operators, using the DEAP library.

## 5.2.1 Creation, evaluation and selection procedure

The description of main steps, parameters and genetic operators used for creating the three optimization variants are presented below.

### Creation and initialization procedure

The initialization procedure creates the first population, which will contain a fix number of individuals, i.e. sequences. The creation of this population can be done randomly (see [Listing B.7](#)) or by using an smart generation method (see [Listing B.8](#)). The smart generation method generates individuals with a total costs value, that is already not above a certain user defined percentage threshold. The individuals are better than the threshold multiplied by the optimal costs. The optimal costs are the result of the costs originated by the default sequence.

### Evaluation function - Environment

Within this single objective problem, the evaluation function will be based on the total transport costs  $P$  for the respective order sequence and on a penalty for not assigned orders. This costs  $P(sequence)$  are calculated using the Equation 4.1, i.e. the objective function presented in chapter 4. Equation 5.1 presents the mathematical description. While Listing B.9 and Listing B.10 in Appendix B present the method for calculating the fitness function and evaluating the population performance.

$$Fitness(sequence) = P(sequence) \cdot (no.orders - no.assignments + 1) \quad (5.1)$$

### Parents selection

After evaluating the population, all parents are listed and sorted starting with the parents with best fitness function, i.e. with minimal costs. Listing B.11 presents the method for getting the  $n_{parents}$  that will be use for crossover and mutation. A set of best parent with the best fitness function will be use for reproduction. Besides, this individual will be present in the next generated population.

For the DEAP Algorithm a classical selection operator from the DEAP Library is chosen *selBest* [DEA09]. This operator select the  $k$  best individuals.

## 5.2.2 Genetic operators - Crossover and mutation

Four types of genetic operators are specifically created for building new order sequences and generate a new population for the next generation. These operators are based on the definition of mutation and crossover operators given by [Koz07]. In [Luk97] a discussion on the benefits of mutation and crossover is given. In the application of genetic programming for the assignment of synchronodal orders, three of them are based on random mutation. While the fourth created operator resembles to the idea of crossover, based on mating between best parents.

Figure 5.5 presents the three different mutation operators for creating new individuals. The methods created for implementing the genetic operators can be found in Appendix B Listings B.12, B.13 and B.14.

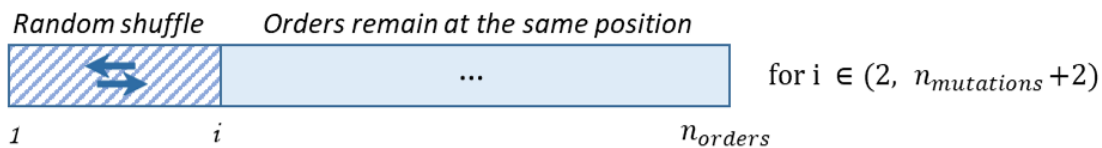
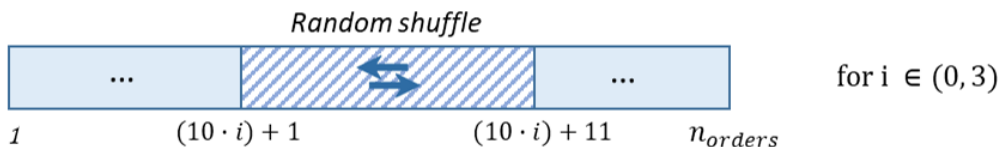
**Mutation operator 1****Mutation operator 2****Mutation operator 3**

FIGURE 5.5: Mutation operators

Figure 5.6 presents the crossover operation created as a recombination of  $i$  best parents: New individuals are created by recombination of common items, between pairs of best parents. Listing 5.5 presents the methods implementing the genetic operator for crossover.

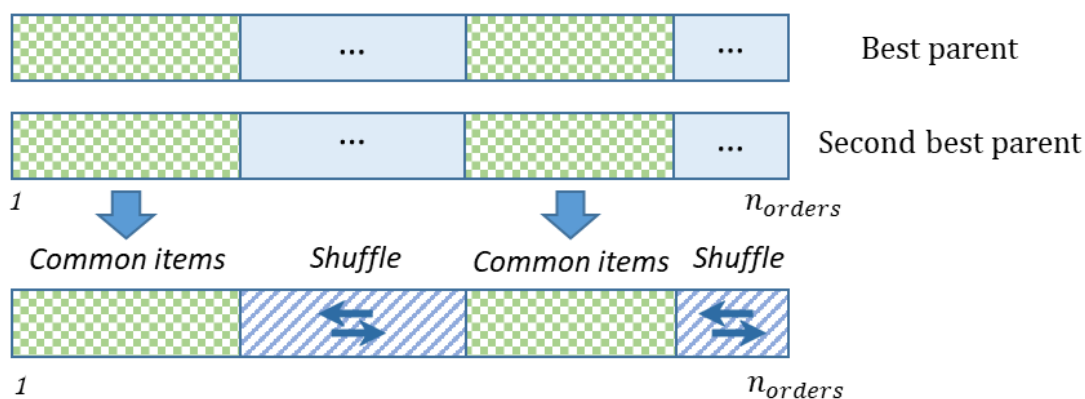
**Crossover operator**

FIGURE 5.6: Crossover operator

LISTING 5.5: Method for mutation operator 4

```
def mutateParents4(parents):
    mutations=[]
```

```

for i in range(len(parents)-1):
for j in range(5):
mutation= supermutation(parents[i],parents[i+1])
if mutation:
mutations.append(mutation)
return mutations

def supermutation(a,b):
intersections=[]
intersections_ind=[]
for i in range(len(a)):
if a[i]==b[i]:
intersections.append(a[i])
intersections_ind.append(i)
if intersections:
rest=shuffleList(list(set(a)-set(intersections)))
for i in range(len(intersections)):
rest.insert(intersections_ind[i],intersections[i])
return rest
else:
return []

```

For the DEAP algorithm following classical operators are chosen: three crossover operators *cxPartiallyMatched* from [Gol85], *cxUniformPartiallyMatched* from [CS00] and *cxOrdered* from [Gol12] and one mutation operator *mutShuffleIndexes* from [DEA09].

## 5.3 Multi-objective optimization of synchronodal transport planning

A multi-objective optimization problem deals with the optimization requirements of two or more objectives which might be in conflict. This situation generates a problem which usually will not contain a single optimal solution, but a finite set of optimal solutions. Thus one solution will always be a compromise between optimization objectives. The output of genetic algorithms are a set of Pareto optimal solutions or Pareto front, i.e. local optimal solutions where the improvement of an objective is not possible without deteriorating another objective at the same time.

The use of genetic algorithms for solving multi-objective optimization problems is well known. The motivation for using EAs in multi-objective optimization problems is the possibility to simultaneously evaluate a set of solutions, i.e. populations, and to better deal with the continuity and concavity of the Pareto front [CL04].

In transport and logistic sector decisions are mostly taken based on monetary aspects and the environmental impact plays later a role. However in the past years penalties and fines for exceeding the permitted  $CO_2$  emissions have increased [Pub16]. Transport operators and planners start to be more conscious about the environmental impact factors. In order to meet assignment's decisions minimizing both aspects, the monetary and the environmental impact, a multi-objective optimization algorithm must be solved.

In this work a well-known multi-objective algorithm is chosen, the Non-dominated Sorting Genetic Algorithm (NSGA). This multi-objective genetic-based algorithm was developed in 2002 [Deb+02]. As a genetic optimization algorithm, the objective of the NSGA remains the continuous improvement of population's fitness constrained by a set of objective functions. The results given by the multiple populations are evaluated and sorted in a hierarchical non-dominated Pareto front [Bro12]. This methodology has been for example already used by Halim [HT17] for solving the strategical SND problem of hubs location. Within this work the same approach, NSGA-II will be used for solving tactical and operational routing and assignment problems.

### 5.3.1 NSGA II Procedure

The procedure of the NSGA II is shown in Figure 5.7 and its implementation can be found in Listing B.15. The algorithm uses an evolutionary process containing genetic operators for selection, crossover and mutation. The operators used for crossover and mutation are classical genetic operators. The same genetic operators have been implemented in section 5.2 for the single objective optimization using DEAP library. The method of selection is special for NSGA-II based on average distance between members of each front. The solutions are ranked regarding their dominance of the front to which they belong. Then the algorithm will discriminate the members of the population first by rank and in a second step by the distance within the front [Bro12].

### 5.3.2 Evaluation function

The evaluation function for the generated individuals, i.e. orders' sequences, is the same as for the single objective problem (see 5.2).

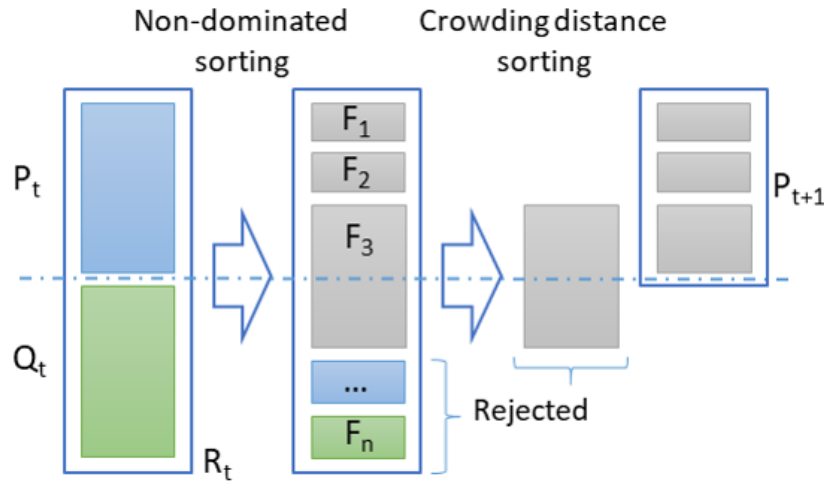


FIGURE 5.7: NSGA-II procedure based on [Deb+02]

$$Fitness(sequence) = P(sequence) \cdot (no.orders - no.assignments + 1) \quad (5.2)$$

The fitness function defined for the single objective (4.1) is split by its two summations as shown in 5.3 and 5.4.

$$P_{(sequence)} = \sum_{o \in O} \sum_{s \in S} X^{so} \cdot C^s + \sum_{j \in N} \cdot n_j \cdot T_c \quad (5.3)$$

$$P_{Impact}(sequence) = W_E \left( \sum_{o \in O} \sum_{s \in S} X^{so} \cdot E^s + \sum_{j \in N} \cdot n_j \cdot E_j \right) \quad (5.4)$$

## 5.4 Summary

In this chapter three optimization algorithms have been developed for solving the flexible orders' assignment problem. The output of the model is an optimal routing and service selection, using the remaining free transport capacity. Besides, as presented in chapter 4, two types of flexibility can be simulated (capacity and time delivery).

Two single objective optimization algorithms have been developed. The first algorithm delivers the best orders' assignment from a local perspective following a FIFO approach, while the second follows a GA approach. three variants of the single objective GA are proposed: a random generation using own developed genetic operators, a smart generation using the same own developed genetic operators and a random generation using classical genetic algorithms from the DEAP library.

Finally, a multi-objective optimization approach, the NSGA-II is presented for optimizing the orders' assignment decision regarding monetary costs and environmental impact separately. The test and evaluation of all the different introduced approaches for planning synchromodal services are presented in [chapter 6](#).

## Chapter 6

# Application Scenarios

The synchronodal transport model introduced in [chapter 4](#) for a dynamic transport planning will be implemented and tested in this chapter. Besides, the optimization methods and algorithms presented in the fourth and fifth chapter will be applied to three different application scenarios. The goal of this section is to proof, that the model, including the underlying methodology, leads to better intermodal freight transport decisions, when planning synchronodal transport services from a tactical and operational point of view.

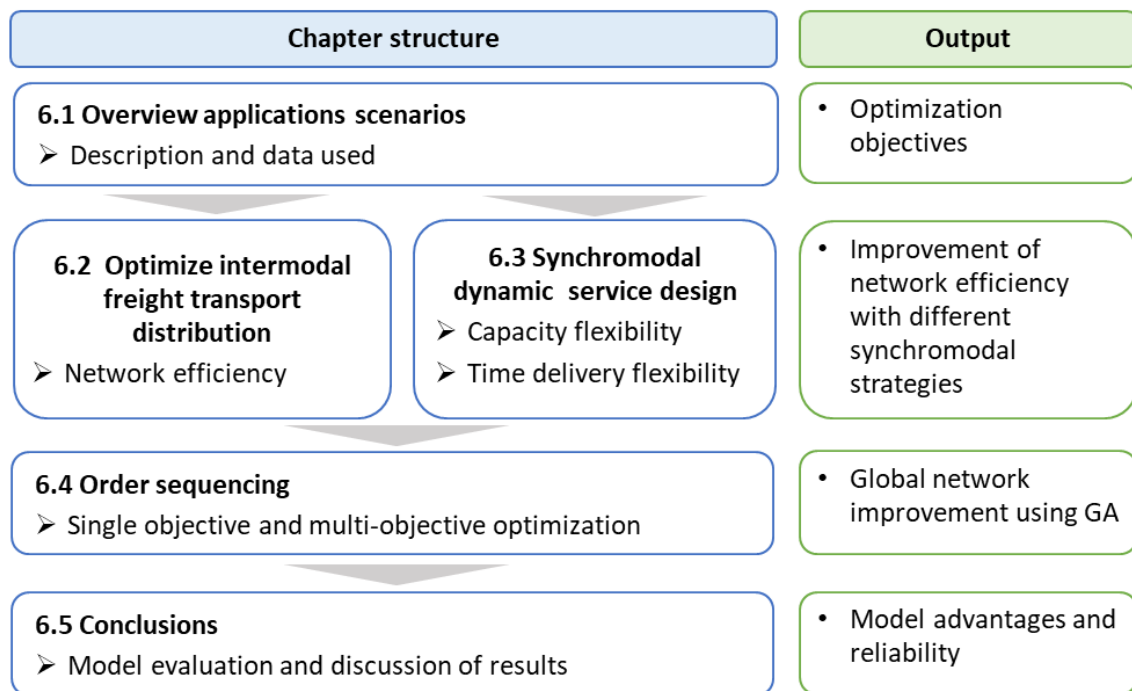


FIGURE 6.1: Chapter 6 structure and content flow

[Figure 6.1](#) presents the chapter's structure and the order of implementation of the

different application scenarios. The parameters' setting of the model enables the simulation of different transport planning scenarios. The analysis of the results highlights the benefits when creating and promoting synchromodal transport services.

## 6.1 Overview of applications scenarios

The synchromodal model and the different optimization approaches presented in [chapter 5](#) are applied to a transport network, based on current public information. Two main objectives are followed in this section. On one hand, the potential for a modal shift, when using the proposed model, will be presented. On the other hand, the analysis will show the global improvement of the network efficiency in terms of resources' utilization, costs and environmental impact, when applying this synchromodal approach.

Following three application scenarios for the synchromodal transport model and transport planning scenarios are presented in the corresponding sections of this chapter:

### 1. Optimize intermodal freight transport distribution

Within this scenario the simulation and results of synchromodal orders assignment in an IFTN is shown. Objective of the model is to achieve a modal shift from road to rail and barge enhancing intermodal transport capacity efficiency in a hinterland transport network. All network services and resources will be considered as a whole system as mentioned in [chapter 4](#).

### 2. Synchromodal dynamic service design

Based on the first application scenario, the concept of schedules' flexibility and independencies of services is added to increase the network's efficiency.

### 3. Decision support for order sequencing with genetic optimization

A further extension of the model enables the simulation of optimal routing solutions and order assignments for single and multi-objective problems, such as the sometimes conflicting objectives of monetary cost and environmental impact.

All three scenarios are implemented based on the same database ([Appendix C](#)) and on the model presented in [chapter 4](#). The database contains following main sources of information: Two dynamic databases, the in-coming shipment orders and the intermodal freight transport services, are being updated at each moment that a change occurs, for example after a container assignment or a change of capacity or time schedule of a certain transport service. The static source contains constant network information

(terminal sizes, distances, maximum capacities, etc.) as well as costs and environmental factors.

Transport data has been gathered from different sources: From the private sector (e.g. transport demand), governmental institutions (e.g. the annual numbers of container flow between multimodal terminals), as well as public resources (e.g. the public available schedules from main container terminals). The data use for the evaluation and test of the model is attached in [Appendix C](#) and divided in 42 in-coming customers' orders with a total of 97 container and 94 multimodal transport services. The monetary costs considered for each service (see [Figure C.4](#) and [Figure C.5](#)) are calculated using the developed costs model presented in [chapter 4](#). The feasibility of these costs is confirmed by comparing the obtained transport prices to the prices given by [[Con18](#)] and the tkm price presented in [[Dem+15](#)]. The way all modules were implemented enables the model's easy adaption and scalability to other specific application scenarios.

The subject of investigation is a network composed by the three biggest container ports in Europe (Rotterdam, Hamburg and Antwerp) and eight intermodal terminals located in the hinterland region of North Rhine-Westphalia (NRW): Duisburg, Dortmund, Cologne, Neuss, Duesseldorf. [Figure 6.2](#) presents the transport network used as test bed for simulating the different application scenarios. For simulating the three different scenarios listed above, data was used based on real current transport services schedules from all five intermodal terminals and tree port terminals.

It is important to remark that all results presented in this chapter have as basis input the transport network of services and customer's orders presented in [Appendix C](#). Even if the values of the scenario has been set as real as possible, the absolute results are not as relevant as the relative values. As benchmark value, the transport by road is selected considering that customers' orders are transported by truck.

## 6.2 Optimize intermodal freight transport distribution

### 6.2.1 Problem description

The modal split within the hinterland territory of major ports does not match with the objectives set by the governments. As describe in [chapter 2](#), in its white paper the European Commission set the goal to shift 30 % of road freight over 300 km to other modes, such as rail or waterborne transport by 2030, and more than 50 % by 2050

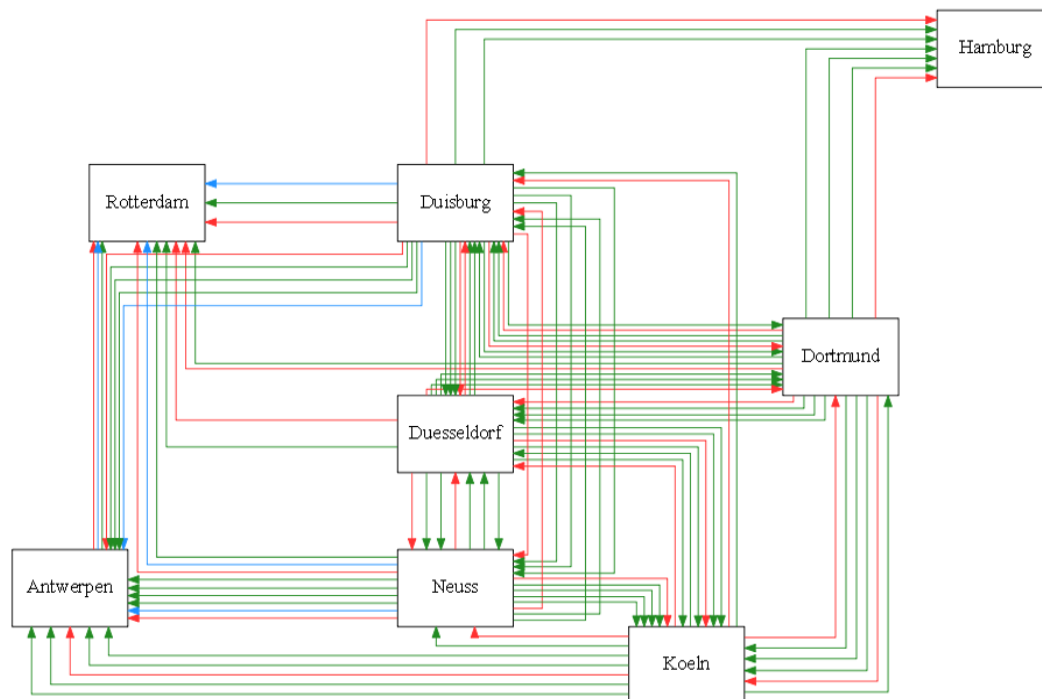


FIGURE 6.2: Network of intermodal services (train, barge and truck services are represented by red, blue and green lines respectively)

[Eur11]. In this use case the potential shift from road transport to unused transport capacities in rail and waterway is shown by the means of offering synchromodal services to an intermodal transport network. Therefore, the application scenario explores the efficiency of modes' utilization when enabling a synchromodal transfer between different transport services. The challenge is to allocate truck orders, i.e. road transported loading units, in free train or barge capacity slots.

The current intermodal transport network in Europe is not used in a cooperatively way and the information of capacities and utilization between the different transport operators, transport modes and costumers is not shared. This generates a sub-optimal distribution of cargo within the offered transport resources. Due to this effect the most flexible mode of transport, road transport, is being selected by costumers to realize the transport, even if free capacities are available in the other two modes of transport. With the development of a synchromodal network, the efficient utilization of transport resources increases, while supporting the utilization of more environmental friendly transport modes by shifting the road transport to train or barge.

### 6.2.2 Implementation

A transport network consisting of roadway, railway and waterway is considered for obtaining a freight transport plan to deliver cargo shipment from origin to destination with multiple and flexible transshipment points along the routes. As a constraint, the freight of a customer's order cannot be split at a transshipment terminal. At a scheduled start time a specific freight enters the transport network at a origin terminal. The network is capacitated based on on number of TEU free slots in transport services and considers specific schedules (flexible or not) for the available transport services.

A optimized path between origin and destination is not achieved by only computing the shortest path. Instead, cost- and environmental impacts between origin and destination pairs are computed for all possible shortest paths. For dimensional similarity in a single objective optimization problem, the various environmental impacts are converted to monetary value. The sum of monetary and environmental costs is chosen as weight factor across the network graph, so that all feasible transport routes between origin and destination are iteratively evaluated using the calculated weight. The transport route with the lowest weight complying with all restriction is selected as the proposed route, so that all customers' orders get assigned to a set of intermodal transport services.

Following steps are taken for shifting truck shipments to available free slots in barge or train within the considered intermodal network:

- Simulation of the network's capacity and transport resources schedules. The available intermodal transport resources are composed of free slots in train and barge scheduled services. For the simulation of the initial planned network distribution, one representative weekly schedule of barge and train services is considered. A limited number of truck services with flexible time are considered, enabling the delivery of all shipments as well as their pre and post-carriage.
- Collect information about customer's orders.
- Matching barge and train schedules with new truck shipments, while keeping origin-destination pairs as wished by cargo owners.
- Optimize the routing of new orders, selecting optimal transport services with free slots. These assignments of orders, i.e. container allocations, occur for the minimum costs at the time of decision following a FIFO approach.

TABLE 6.1: Main model input parameters

Parameter	Value
Orders	97 loading units in 42 customers' orders can be found in Appendix C Figure C.1
Services	94 intermodal transport services can be found in C Figure C.2, Figure C.3, Figure C.4 and Figure C.5
Order sequence	Order's departure time
$W_e$	€0,1 (i.e. 100 kg/ $CO_2 - Eq.$ )
$T_{max}$	2 transshipments
N	3 (as cut-off value for all simple paths algorithm)
TEU	Average of 16t payload as a conversion value

- If an order can not be assigned, a penalty factor is set for transporting the cargo. This penalty simulates the option of an expensive subcontracted transport by truck with factor 2 €/km.

The synchromodal assignment optimization algorithm presented in section 5.1 is used in combination with the input parameters and data presented in Table 6.1.

### 6.2.3 Results

The output of this analysis is the cargo flow within the transport network for the considered customers' orders. Figure 6.3 shows the cumulative costs generated while assigning all transport orders following the FIFO approach shown in Figure 5.3, where customers' orders have been sorted by increasing departure time.

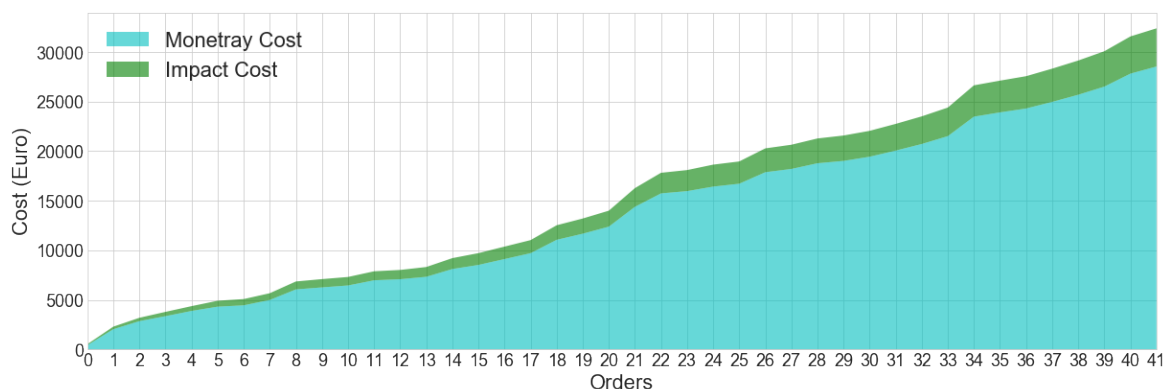


FIGURE 6.3: Cumulative costs generated through the assignment of 42 orders and split between monetary and environmental costs (0,1 €/t  $CO_2$ -E.q)

The total cumulative costs for the transportation of 97 loading units is calculated at a cost of €32.378,15 within the presented intermodal transport network of which €3.847,06 are produced by the emissions of  $CO_2$ -Eq. The same orders could be transported by truck generating a cost of €55.748,35, thus a saving of €23.370,20 can be realized when using a synchromodal approach.

## 6.3 Synchromodal dynamic service design

### 6.3.1 Problem description

As discussed in [chapter 3](#) (see [Table 3.5](#)) the idea of synchromodality requires dynamic transport planning and the ability to flexibly adapt the service network characteristics to real time changes. For this reason it is not enough to plan transport in an intermodal manner. It is essential to allow a certain flexibility within the transport network, both in the transport service and in the client's transport conditions.

The application scenario presented in this section elucidates how the developed model can be used to explore the efficiency of the network under certain conditions. By doing so the necessary conditions for promoting and improving intermodal transport will become visible.

### 6.3.2 Implementation

In order to simulate the flexibility in time regarding the delivery of orders and the flexibility in a transport service's capacity, nine scenarios are tested. [Table 6.2](#) presents the scenarios that will put the developed model to test regarding its ability to improve orders' assignments, i.e. the cargo distribution. The scenarios are a combination of three sequence possibilities of transport orders and two flexibility values: On one hand the possibility that customers allow some extra time for delivery and on the other hand the possibility to extend the capacity of some transport services. In this way the robustness of the network regarding the variability and uncertainty of transport demand will be proofed.

TABLE 6.2: Flexibility scenarios

Scenarios	Order sequencing	Flexibility options
TD-NF	Departure time (TD)	No flexibility
TD-TF	Departure time (TD)	Order's delivery time flexibility
TD-TEUF	Departure time (TD)	Services' capacity flexibility (TEUF)
TA-NF	Arrival time (TA)	No flexibility
TA-TF	Arrival time (TA)	Order's delivery time flexibility
TA-TEUF	Arrival time (TA)	Services' capacity flexibility (TEUF)
Random-NF	Random sequence	No flexibility
Random-TF	Random sequence	Order's delivery time flexibility
Random-TEUF	Random sequence	Services' capacity flexibility (TEUF)

### 6.3.3 Results

The results of all nine scenarios are presented in [Table 6.3](#). The minimum costs are achieved when some extra capacity is given to certain services (see column *capacity flexibility* in [Figure C.3](#), [Figure C.4](#)). The algorithm assigns the order's to the cheapest transport service combination. This scenario helps in the decision of singular service' capacity, when considering the whole transport network.

TABLE 6.3: Comparison of all scenarios

Scenario	Total costs (€)	Env. Impact ( $CO_2 - Eq.$ )	Penalties	Saving (%)
TD-NF	32.378,15	38.470,65	0	42
TD-TF	31.052,01	36.462,79	0	44
TD-TEUF	26.805,22	31.370,18	0	52
TA-NF	32.079,18	37.951,28	4	42
TA-TF	31.407,29	37.198,81	2	44
TA-TEUF	26.805,22	31.370,18	0	52
Random-NF	32.048,85	37.686,97	0	43
Random-TF	31.568,99	37.165,46	0	43
Random-TEUF	26.805,22	31.370,18	0	52

The different costs' values within the scenario TD-TA-Random show the importance of orders' sequencing. Since customers' orders can not be split and the optimization follows a FIFO approach, a transport service might be used more efficiently to transport larger cargo from another customer's order or a combination of (unsplitted) orders.

Figure 6.4 presents the cumulative costs generated in the three different flexibility scenarios, all of them calculated with the order sequence sorted by time of departure. For the exemplary data used, an improvement of the global costs can be seen, when increasing transport capacity as well as allowing a later delivery time for some customers' orders (see column *Time to deliver (flex)* in Figure C.1). These settings enables the user to obtain the services with major demand.

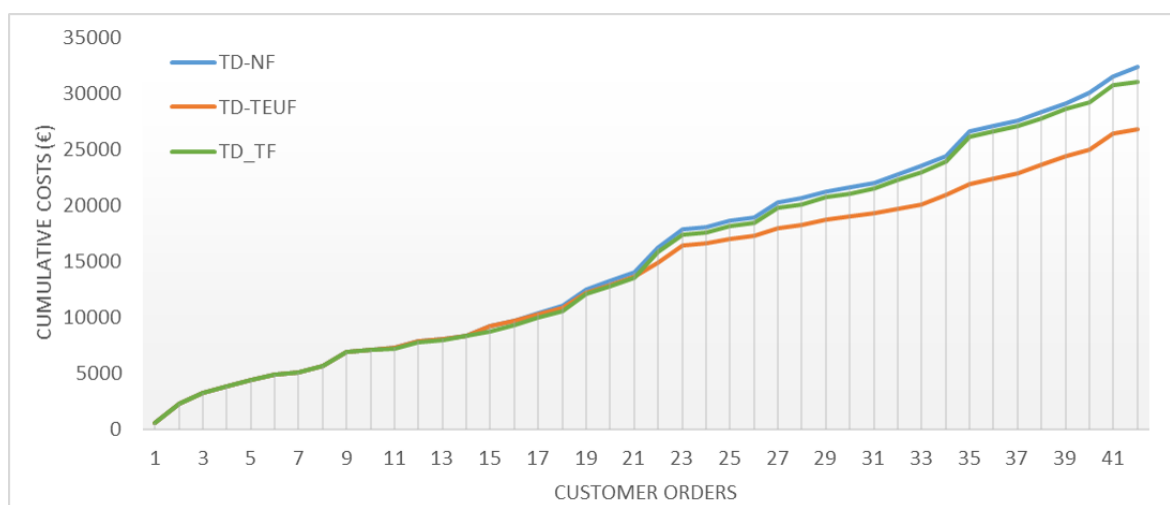


FIGURE 6.4: Cumulative costs generated between three different network scenarios

The improvement of the modal split through the different flexibility scenarios can be seen in Figure 6.5. A comparison of the scenario without flexibility (TD-NF) and the two flexibility scenarios (TD-TEUF and TD-TF) shows, that the developed optimization model supports a better modal split of the transport network.

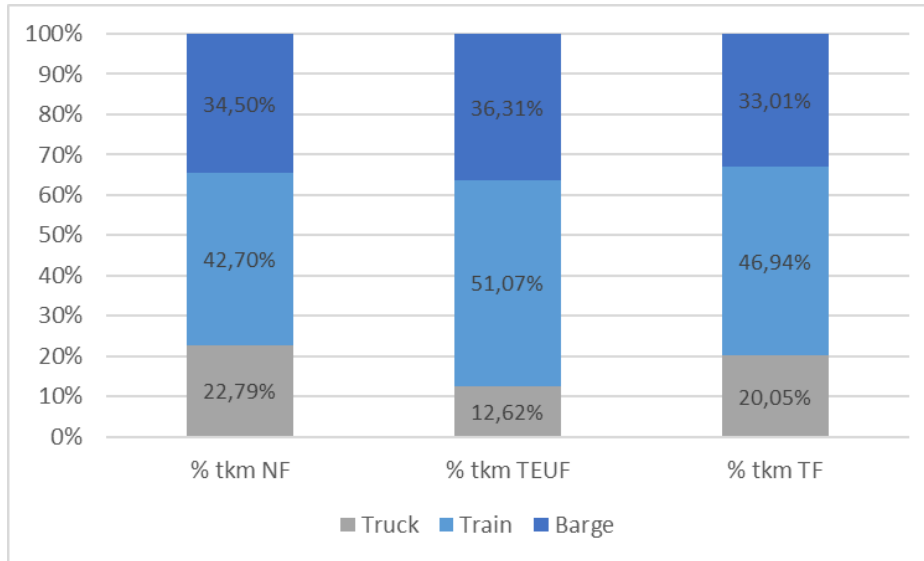


FIGURE 6.5: Percentage of transport mode utilization for the scenario with order's sequencing by departure time (TD)

The results presented in this section demonstrate the significant improvement potential:

- Increase of intermodal transport service utilization ranging from 2,7% with time flexibility to 10,1% when increasing the transport capacity. This demonstrate the importance of flexibility and adaptability of transport conditions.
- Monetary costs and environmental savings up to 50% with respect to road transport.
- Importance of uncertainty in demand and order's sequencing.

## 6.4 Genetic optimization for order sequencing

In order to investigate optimal sequence possibilities GA is used for exploring the solution space. The results of the implementation of the three developed methods presented in [section 5.2](#) and [section 5.3](#) are shown in this section.

### 6.4.1 Single objective genetic optimization

All three genetic based optimization methods use the same algorithm for order assignment, the same data (see Appendix [Appendix C](#)) and have the same fitness function. The algorithm for the assignment of orders has been presented in [chapter 4](#), while

relevant python code presenting the implementation of the different methods has been presented in [chapter 5](#). On the one hand, the methods Random and Smart generation use the same genetic operators, but differ regarding the initialization procedure. On the other hand, the method DEAP applies classic genetic operators. The operators have been presented also in [section 5.2](#).

TABLE 6.4: Evaluation results for three different GA methods with  $p_{size} = 100$

Method	$n_{gen.}$	$n_{tests}$	Abs. Min. Costs (€)	Avg. Avg. Costs (€)	Avg. Time (it/s)	Sequence
Random	200	1	30.980,8	39.821,9	12,84	[28, 12, 27, 5, 26, 1, 6, 20, 0, 3, 16, 8, 41, 23, 36, 22, 18, 10, 33, 21, 29, 7, 14, 13, 37, 24, 19, 30, 9, 38, 4, 11, 40, 34, 35, 39, 2, 32, 31, 15, 25, 17]
Smart Gener- ation	200	1	30.996,8	31.645,3	26,92	[9, 19, 0, 36, 6, 10, 35, 22, 1, 3, 33, 13, 7, 21, 8, 23, 30, 29, 4, 26, 28, 11, 5, 25, 24, 18, 40, 34, 41, 20, 2, 32, 16, 12, 27, 37, 38, 15, 14, 31, 17, 39]
DEAP Opera- tors	200	1	30.991,9	50.106,2	12,81	[3, 27, 5, 22, 11, 4, 16, 38, 28, 30, 24, 25, 26, 34, 17, 39, 18, 14, 2, 8, 37, 33, 1, 6, 10, 23, 21, 41, 20, 12, 32, 35, 0, 36, 9, 7, 29, 19, 13, 15, 40, 31]

[Table 6.4](#) presents an overview of the results when selecting the best order sequence and the resulting generated costs, using the same assignment algorithm as in [section 6.3](#). The three GA methods are evaluated for a population size of 100 individuals, 200 generations and only one test. The absolute minimum costs (Abs. Min. Costs) denotes the minimum value achieved by the best individual in all generations. The value of Avg. Avg. Costs denotes the average of all generations population costs' average.

The minimum costs solution is achieved using random initialization and the genetic operators developed by the author. This method allocates all 42 orders within the

created synchronodal network for a total costs of €30.980,8 , thus improving the global transport costs by €1.068,05 with respect to the FIFO assignment and the order sequencing by departure time (Figure 6.3).

Regarding their computational time, the iteration per second are very similar when using random and DEAP methods, with an average time of 12,84 it/s. These calculations have been done with an intel core i7 processor. The possibilities to improve the calculation time will be discussed in chapter 7.

All three methods converge towards a minimum costs close to €31.000. For the test presented in Table 6.4, the development of minimum cumulative costs of the best individual are presented in Figure 6.6 for all three methods. The minimum cumulative costs is achieved in all three methods already before 100 generations.

Figure 6.7 represents the population costs' average per generation. When comparing the shape of the curves, it can be seen that the smart generation method converges faster than the rest. But the similar cumulative costs over all generations seen in Figure 6.7 prove, that the method stagnates at a local minimum due to its low population variability.

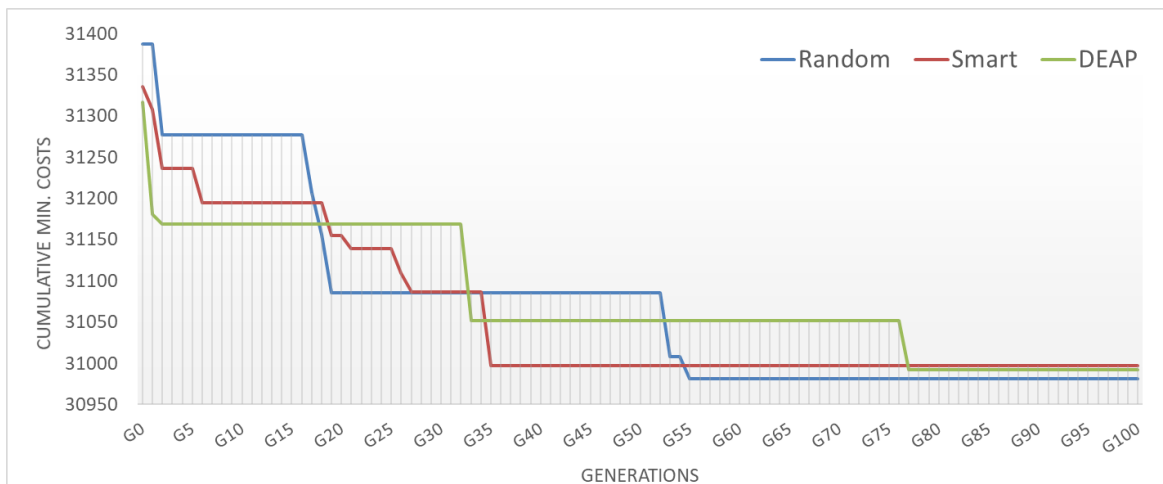


FIGURE 6.6: Evaluation of GA method: Absolute minimum cumulative costs

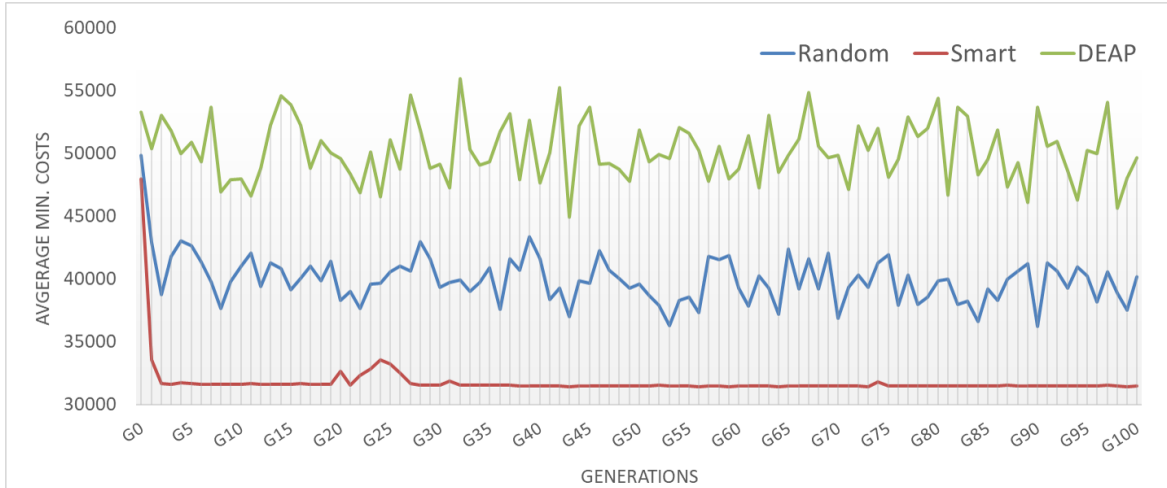


FIGURE 6.7: Evaluation of GA methods: Average minimum cumulative costs

Since all three methods are stochastic, a higher number of tests than one as in [Table 6.4](#) should be performed, in order to select the best solution out of all tests. [Table 6.5](#) and [Figure 6.8](#) presents an extract of the results for different tests by DEAP and Random methods. The smart generation method has not been listed, as it under-performed in finding the optimal solution compared with the two listed methods. As can be seen the absolute minimum costs are smaller when the optimization is calculated for 100 generations.

TABLE 6.5: Evaluation results with multiple test with GA method  
Random and DEAP with  $p_{size} = 100$

Method	$n_{gen.}$	$n_{tests}$	Best test	Abs. Min. Costs (€)	Avg. Costs (€) best test
Random	50	20	T10	30.894,33	39.850,10
Random	100	20	T7	30.936,43	31.012,09
DEAP	50	20	T17	30.983,25	45.337,36
DEAP	100	20	T10	30981,105	45.126,62

The minimum cumulative costs in the 60 tests carried out is achieved by the random method and has a value of €30.894,33. [Figure 6.8](#) shows all absolute minimum cumulative costs for each test. Even if the order sequence differ greatly between the different methods used, the results shows that the optimal services selected are very similar.

[Figure 6.9](#) presents the services used, marked with color, for the random sequence with minimum value. The numbers in [Figure 6.9](#) denote the remaining free capacity, where

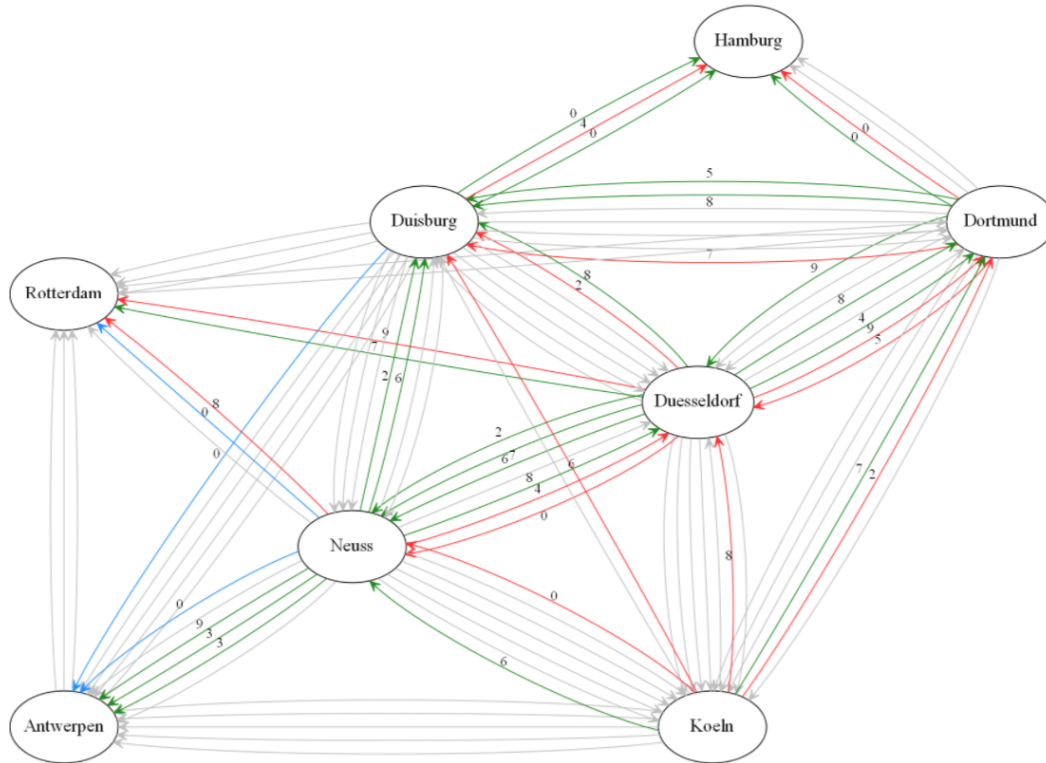


FIGURE 6.9: Network of synchromodal services, with remaining capacities (train, barge and truck services are represented by red, blue and green lines respectively)

following sequence has been selected: 1, 3, 4, 5, 6, 10, 12, 13, 14, 15, 17, 18, 20, 22, 24, 25, 27, 28, 29, 30, 38, 39, 45, 47, 48, 49, 50, 53, 54, 55, 57, 58, 59, 60, 87, 88, 89. In C.6 the assignments results are shown.

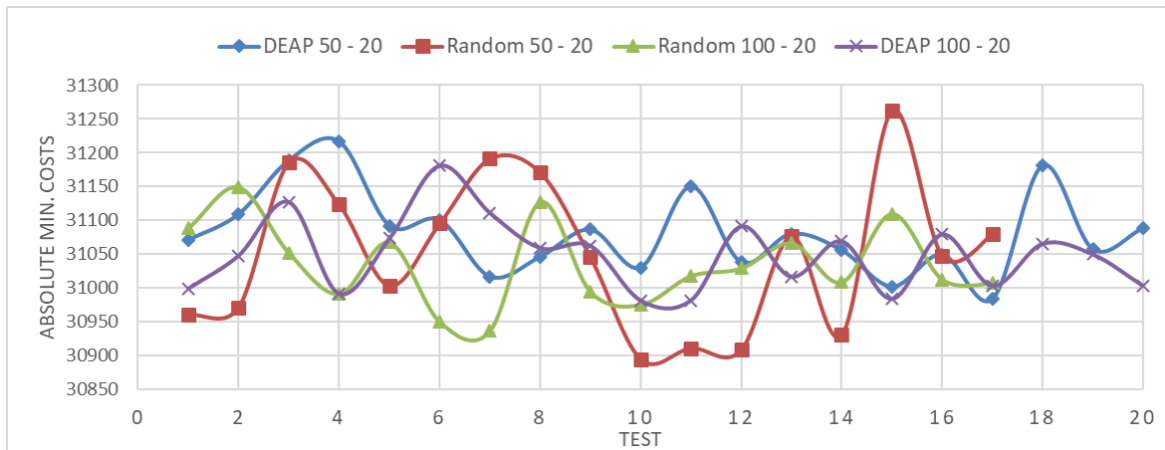


FIGURE 6.8: Minimum cumulative costs for GA optimization using Random and DEAP operators for 20 tests

## 6.4.2 Multi-objective genetic optimization

In order to detect the best network distribution and order's assignment for minimum monetary costs and minimum environmental impact a multi-objective decisions problem must be solved. For solving this multi-objective decision problem the NSGA-II algorithm presented in [section 5.3](#) is used. [Figure 6.10](#) and [Figure 6.11](#) show the results when applying the NSGA-II algorithm with following parameters setting:  $n_{gen.} = 100$ ,  $I_{size} = 42$  (individual size),  $p_{size} = 100$ .

It should be noted that the genetic operators for mutation and crossover are the same as the ones used in DEAP SOOA method presented before.

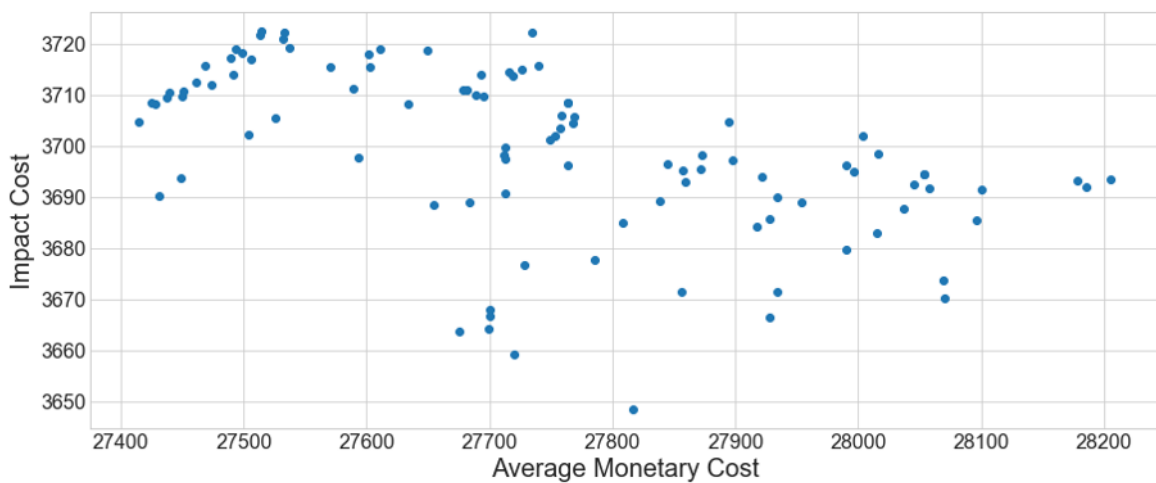


FIGURE 6.10: Solutions generated by the NSGA-II for the average monetary costs (in €) vs. environmental impact (in €, assuming 0,1 €/per kgCO<sub>2</sub>-Eq.)

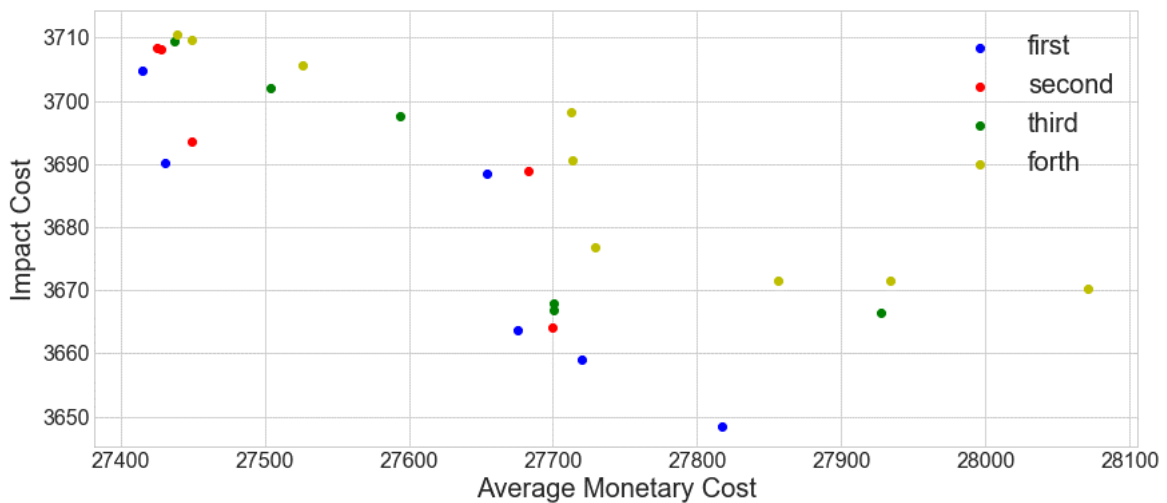


FIGURE 6.11: Solutions generated by the NSGA-II sorted by the belonging to a Pareto-front

The best element in all generations has the order sequence [38, 17, 16, 4, 20, 5, 22, 3, 10, 28, 1, 32, 26, 6, 8, 21, 7, 13, 30, 11, 18, 41, 19, 14, 34, 35, 23, 31, 27, 25, 29, 40, 33, 15, 36, 37, 2, 0, 24, 39, 12, 9] and total cumulative costs of €31.119,61, of which €27430.73 are monetary costs and €3.690,20 environmental impact costs. This results shows that this method also achieve an optimization near to €31.100, but due to its selection process it does not achieved a global minimum better than the single objective optimization with DEAP and random methods.

## 6.5 Summary

This chapter has presented the results of three different application scenarios for the developed model, using the same transport data and main settings for all of them:

1. Optimized intermodal freight transport distribution: By using the algorithm presented in [section 5.1](#) a local optimization of orders' assignment is achieved. The results show that a saving of 42% of the transport costs can be achieved (for the given transport situation, i.e. data) by using the remaining capacity of the multimodal transport network.
2. Synchromodal dynamic service design: The analysis of different flexibility settings, confirms the reduction of the total network costs as presented in [Table 6.3](#). The flexibility options supports the simulation of possible savings and resource's efficiency improvements when enabling more service capacity or a larger transport time window.
3. Decision support for order sequencing with genetic optimization: For a global optimization of the transport network the GA optimizations proposed in [chapter 5](#) are tested with very good results. The algorithm with the best performance in terms of achieving minimum costs, is the random approach using the own developed genetic operators. The DEAP method achieves also good results, but needs more generations for achieving the same results. Finally NSGA-II improves the total costs of the model and is faster in its execution, but the optimization's results regarding the absolute minimum are worse than the other approaches.

In all cases the output of the model is a selection of optimal transport services, for transporting customers' orders, thus defining the routing and distribution of cargo. The setting of services and orders characteristics as well as the setting of model parameters for the optimization algorithm and for the calculation of monetary costs and environmental impact, allows a large variety of investigations.

## Chapter 7

# Transfer and extension of the model

After the developed model has been put to test in [chapter 6](#) with promising results for improving the planning of a synchromodal transport network, this chapter will discuss further possibilities of model development and its transferability to other research areas. In this context, the anticipation of the developments in the field of freight transport in the upcoming years is of importance and will be discussed at the beginning of this chapter. To get an overview, [Figure 7.1](#) presents the structure of this chapter and its main output.

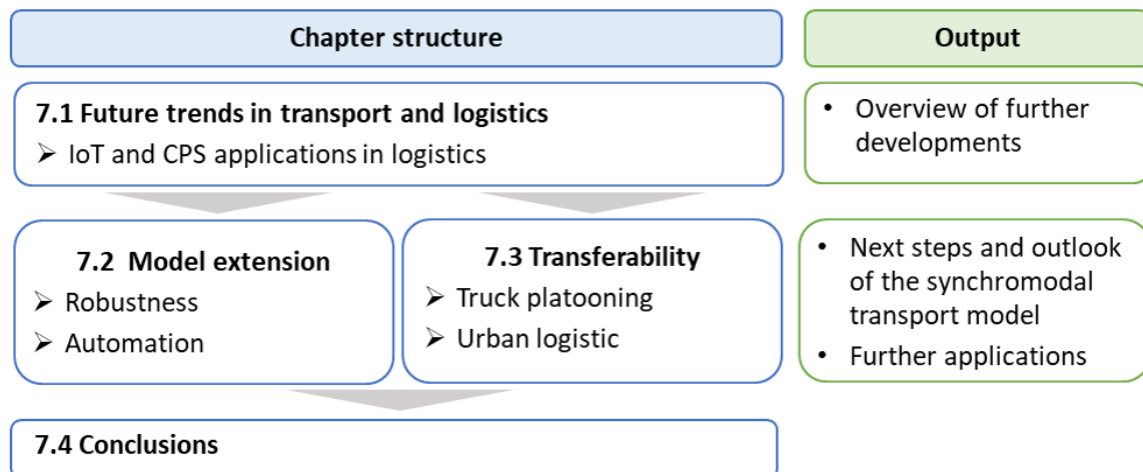


FIGURE 7.1: Chapter's structure and content

In the following, the extension of the synchromodal modal will be discussed in order to lay out next implementation steps for improving the results, as well as for the automation of the model's use in real transport operations. The possible application of machine learning approaches is a promising extension to the model for a better transport planning. The necessary requirements for and the discussion about the

methodology of machine learning will be addressed in this chapter. Finally, the transferability of the model will be shown by applying the model to other fields like fleet management in truck platooning.

## 7.1 Future trends in transport and logistics

The future of logistics, commonly known as logistics 4.0, can be split in five areas of main focus: digitalization, network collaboration, service-level extension, green and sustainable logistics and automation of supply chain [Fen17] [Jes17]. All these areas are interconnected to each other, so that the development and competences acquired in one area serve as the fundamentals for the others. The definition for each area of development in logistics 4.0 is given below:

- **Digitalization:** This area addresses the steps of digitizing logistic processes and the creation of digital business. The efficient exchange of relevant process data and the accessibility of useful information are crucial for the improvement, adaptivity and reliability of transport and logistic processes. They enable the creation of the IoT in logistics using digital and communication technologies for collaboration.
- **Network Collaboration:** The efficiency improvement of transport resources' utilization as well as the increase of flexibility and reliability in logistic processes demand for a close collaboration between transport and logistic actors. Synchronomodality is based on this aspect and calls for a general cooperative model to align data exchange, communication and processing of information. The understanding and acceptance of communication standards and protocols enables a seamless communication and collaboration between all participants in the supply chain.
- **Service-level extension:** As a result of the development in other areas, new services can be offered to the customer, ranging from new physical transport connections to live cargo tracking. Digital processes are faster and more transparent. They enable a user centered design of new services, for example through APIs, and change the future customer relations. This change has mostly been seen in the consumer sector, where it brought new business areas.
- **Green logistics and sustainable transport:** The environmental impact of transport and logistic needs to be minimized. All technological developments being realized currently address the reduction of carbon emissions through e.g. savings in fuel consumption or improving the aerodynamic of vehicles. Meanwhile, the

transport network itself has not received the same attention in order to grow its sustainability in terms of environmental, economical and social aspects. The use of free multimodal transport capacity, the elimination of empty trips, the use of electrical vehicles or the reduction of traffic jams through a better balanced modal split, are just a few possibilities for how to create a more sustainable system.

- Automation of supply chain: a broader view of all business operations of a company becomes possible, when a digital, cooperative and sustainable way of organizing and performing logistics processes is aimed. This oversight leads to a more extensive vertical and horizontal collaboration between competitors and partners from other sectors. The external and the inner logistics processes will melt in order to deliver a consistent supply chain.

These developments will strongly change how logistic processes are handled and synchromodal networks will demand more and more sophisticated and faster transportation planning models. Thanks to the amount of gathered information and data, new possibilities to deal with these challenges will become available. These new possibilities can be used to extend the model presented in this work.

## 7.2 Critical discussion and model extension

The model presented in this work has demonstrate to be a suitable decision support tool when analyzing the services network design with synchromodal services. The obtained values for optimizing the cargo distribution and the analysis of flexibility approaches in capacity and time are important features needed when planning synchromodal transport services. The results have shown that the model represents a successful approach. However, the evaluation has been done with a small amount of experimental data (compared to the amount of services and orders in a real transport network). Thus, in order to improve its future application, some improvements in the two following areas should be addressed:

- Model scalability and automation of enrichment, setting and visualization processes.
- Further development of optimization algorithms and use of machine learning for increasing algorithm adaptability

The infrastructure for acquiring, integrating and enriching the required data should be build and automatized in order to enable a near to real time evaluation of results. For

the same reason, the visualization and common scenario analysis should be automated. Besides, two main approaches should be addressed in a future work to decrease the calculation time of the GAs and to enable the scalability of the model to larger transport networks: parallel programming and multithreading. The evaluation of each individual is the most time-consuming step of the model. Within parallel programming, the evaluation of individuals can be split between different processors, while within a multithreading approach multiple processes can be executed simultaneously.

The application of machine learning algorithms to the developed model represents a possible extension for improving its adaptability to new transport situations. The approach of machine learning algorithms are in their origin also genetic based and can deal with a large and continuously changing solution space. This aspect, together with the better availability of real time data, promotes the use of these optimization models for transportation planning.

Additionally, these learning algorithms can be very helpful in supporting assignment decisions in freight transportation. Unlike classic optimization models, machine learning algorithms are in most cases faster in their execution, once they have been trained. This factor together with their adaptability, i.e. learning ability, are crucial for a good synchronodal transport model. Figure 7.2 presents an exemplary implementation of machine learning algorithms for developing an assignment model. A reinforcement learning (RL) approach can be used for creating a model that learns from the environment through a reward function.

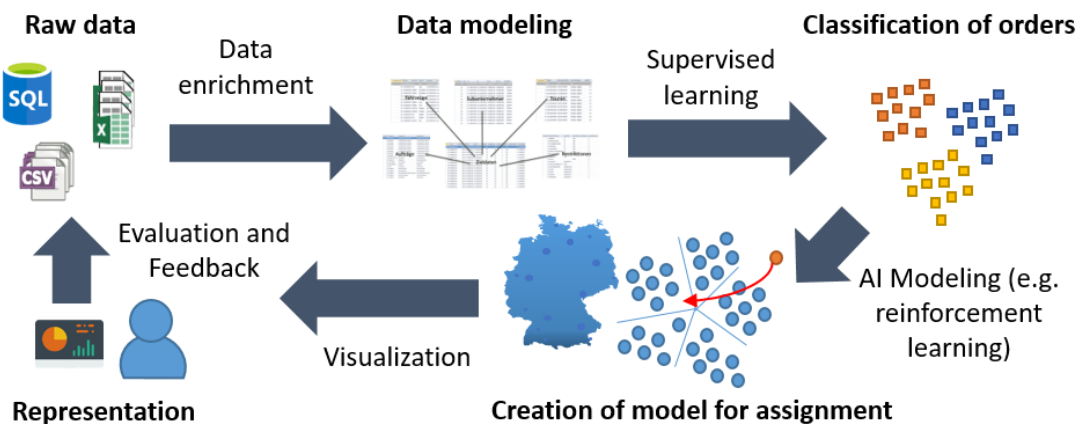


FIGURE 7.2: Machine learning procedure

This approach works similar to genetic algorithms aiming at a better fitness or a greater reward of each cycle or generation [HKP12]. In each cycle, the modified freight cargo distribution is considered, evaluated and rewarded according to its state. An overall

view of all orders and a pre-assessment of the remaining orders serves to ensure a "good" distribution of all orders on "optimal" transport services. Finally, the agent submits the final assignment of orders and services distribution according to the challenges defined within the environment. The benefit of RL algorithms is that they use mathematical frameworks able to develop a policy for maximizing the reward and not only a partially random mutation and selection procedure. One of such frameworks, is a temporal-difference control algorithm known as Q-Learning. Within the Q-learning formulation "the learned action-value function,  $Q$ , directly approximates  $q$ , the optimal action-value function, independent of the policy being followed" [Sut15]. This technique strongly simplifies the analysis of the algorithm and supports its convergence. It should be pointed out that for the use of such reinforcement learning approach the data bases needed have to be large and variable, allowing the algorithm to learn.

### 7.3 Transferability

The synchromodal freight transport model and its approach can be transferred to a lot of similar planning and service design problems in different contexts, like the cooperation within Less-Than-Truckload (LTL) transportation or the transport planning and cooperation between automated guided vehicles in production.

The research on synchromodal transport networks addresses the complexity of the European multimodal logistic system with a high amount of actors, while willing to set more flexible operational processes to better address customer requirements and global network efficiency simultaneously. In opposite to intermodal transport, where the collaboration between all actors is inherent to the system from its very beginning, uni-modal road transport is almost independent from any collaboration. However, this will not longer be the case with the development of autonomous driving. Because of autonomous driving, truck platooning will become reality, forcing all actors in road transport to collaborate intensively.

As prerequisites, the implementation of truck platooning needs further developments in the technology itself and its standards, the road infrastructure allowing V2X communication, development of a regulatory framework, a strengthening of the cooperation between stakeholders and finally political support and incentives [ACE17]. After all these prerequisites are fulfilled, research and testing have to continue, especially regarding multiple brand platooning, the crossing of borders and the reaction of truck platoons in real traffic conditions. Within the last years, a strong effort for the implementation of standardized communication protocols and data exchange has been

set, with the creation of new platforms like ADASIS (Advanced Driver Assistance Systems), SENSORIS (Sensor Interface Specification), TISA (Traveller Information Services Association) or NDS (Navigation Data Standard) [Hub18]. An example for a platform's ecosystem for data exchange in truck platooning is presented by [ERT18] in Figure 7.3.

This kind of platforms will set the basis for the communication and the required data exchange necessary for the realization of truck platooning. As shown in Figure 7.3 new proprietary services will come up. These services will address for example new challenges that arise regarding the orchestration of truck platooning, like fleet management, optimal routing, detection of platooning availability, etc.

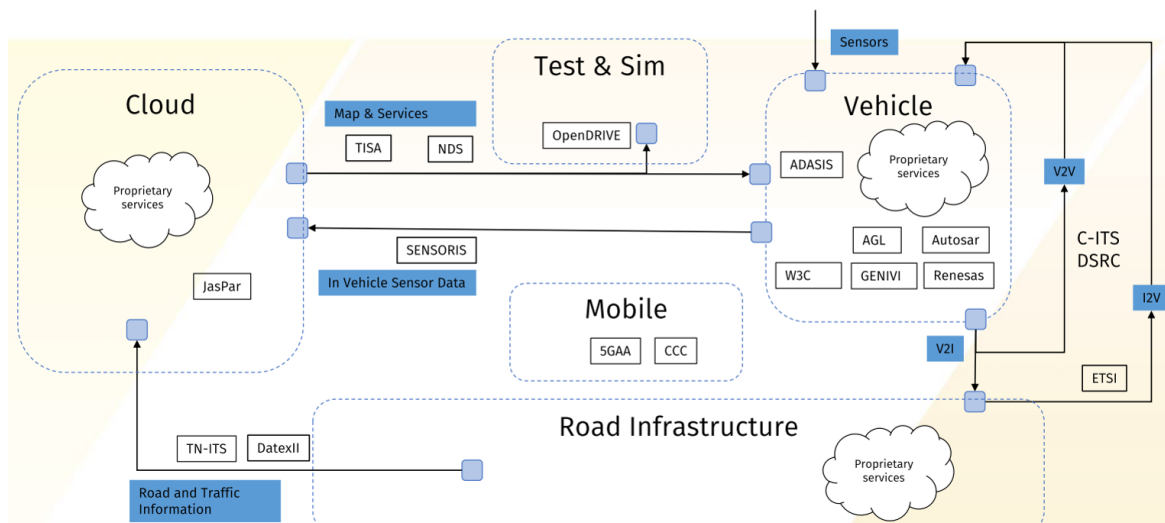


FIGURE 7.3: Exemplary automotive ecosystem for data exchange in truck platooning [ERT18]

As in a synchromodal transport network, fleet management services for the operative planning of truck platooning are crucial to guarantee their implementation in an efficient way. Similar to the characteristics and requirements for synchromodality presented in Table 3.5, the routing of platoons (based on their orders) and the fleet management of truck for building platooning (service design) also requires: a dynamic transport planning dealing with transport variability and uncertainties, real time network information, transparency and data exchange; and optimization algorithm for single units (containers) for the global network (all freight).

The successful management of truck platooning fleets will depend on the determination of the best cooperative routes and on which truck should be assign to it. If properly done, an optimal utilization of the network can be guaranteed not only regarding the flexibility on time, but also on the higher routing flexibility of trucks, similar to the idea behind the mode shifting in synchromodality.

## 7.4 Summary

The overview and description of the future trends in the transport and logistics sector presented in this chapter highlight the need to gain knowledge in the following areas: digitalization, network cooperation, extension of the service level, green and sustainable logistics and the automation of the supply chain.

The synchromodal model created and evaluated within this work will benefit from the research in the above named areas. Based on this future research, some ideas for the model's extension are discussed. A promising extension of the work is the implementation of reinforcement learning algorithms for obtaining optimal assignments. The strong benefit of this approach is its automatically adaptability to changing situations.

In [section 7.2](#), a critical discussion of the model has been presented, highlighting the improvement points for the presented model, like its scalability or an evaluation with more transport data. Finally, the transferability of the model to other applications has been exemplary presented for the use in future planning challenges, when managing truck platooning fleets. To have an efficient distribution of collaborative truck platooning, the services schedules and routing should also be synchronized to build the platoons as efficient as possible.



## Chapter 8

# Conclusions

This last chapter aims to summarize concisely the contribution of this work to the field of multimodal freight transport systems with synchronized services. The achievements of the work as well as current challenges and barriers for the creation of a synchronodal freight transport network are exposed together with an outlook on further research applications.

### 8.1 Summary

Although the dedicated research in synchronodality started only at the begin of this decade, the interest of the transport community, research projects and discussions have exponentially increased in the past three years. The social, economical and political pressure for improving the freight transport system together with the competition of intermodal freight transport, especially rail and waterway transport against road transport, are the main reasons to bet on a change.

The enabler for such a transformation of the intermodal freight transport system is the development connected to the term Logistics 4.0: The constant and rapid improvement of ICT, big data approaches, computing performance and automation. The challenge of synchronizing, aligning and harmonizing multimodal transport services in a cooperative way is a vision that promises the increase of efficiency and competitiveness of the transport sector. Synchronodal transport aims for flexible planning, booking and management of a global and shared network of transport services.

The main contribution of this work is the development of an intermodal freight transport network model supporting a flexible planning of cooperative and synchronized transport services. This synchronodal model enables the simulation of optimal orders assignment's decisions. Based on standardized network information regarding

the characteristics of transport services and orders, an optimization of the cargo distribution has been achieved, helping logistic service providers to decide on routing, mode(s) of transport and orders' assignment.

Further principle achievements of this work can be summarized under the following points:

- The representation of a multimodal transport network, containing main transport information enabling the transport routing and analysis of optimal transport services.
- A general and detailed model for the calculation of generated multimodal freight transport costs in a multimodal network. Following a bottom up approach, principle cost units are taken into account for the main transport modes road, rail and waterway.
- A general model for the calculation of the environmental impact generated during transport processes. The model is created following the life cycle assessment approach during the operation of road, rail and waterway transport vehicles as well as during transshipment processes.
- The creation of a single objective optimization algorithm for order's assignment and transport routing. The algorithm allows the setting of different parameters, like the flexibility of services' capacity and the flexibility in the orders' time of delivery.
- The extension of the single objective algorithm to achieve a better global network efficiency by using genetic algorithms. Therefore, specific genetic operators for mutation and reproduction for the concrete case of cargo assignment are created. Finally, three different implementation settings for the GA are evaluated, presenting very good results in terms of global savings, regarding both monetary costs as well as environmental impact.
- The implementation of NSGA-II for a multi-objective optimization of orders' assignments also using the presented single objective optimization algorithm for transport routing and cargo distribution.

The results of this work lay the foundation for the utilization of different optimization algorithms and settings for the planning of synchromodal services in a multimodal transport network. Furthermore, the model and its algorithms are constructed in a modular and scalable way, so that they can be adapted and extended to other transport networks or situations.

The benefits on a local and global level of the utilization of the multimodal transport network in terms of costs and environmental impact have been presented. This work emphasizes the improvement potential of synchronomodality not only regarding costs, but also regarding the reliability of intermodal transport networks by providing greater adaptability of the services. With these improvements, transport stakeholders are encouraged to seek out for and be part of new business models of cooperation in synchronomodal transport networks.

## 8.2 Outlook

Currently, researchers are working on an implementation of the synchronomodality idea into small scenarios and real transport networks. This work must continue, ensuring the implementation of synchronomodal, i.e flexible and integrated transport as a standard approach to optimize transport systems. The road-map for Europe has been laid out ([chapter 2](#)), but the development of the necessary equipment and communication standards for the needed interoperability between information systems requires some investment and further research. The research developments in the field of IoT in logistics have enormous potential, but the commitment of transport stakeholders remains most probably the major barrier for an extensive implementation. Therefore, government and institutions already working on this topic should further promote this new development in order to push the logistic market to collaborate and create a sustainable and more environmentally friendly transport system for the sake of the whole society.

Further research directions for the development of a synchronomodal transport system are presented below. Each direction addresses different research areas, giving an outlook on the future.

### **Implementation of machine learning for dealing with uncertainties**

Reducing the number of uncertainties is one of the key issues for creating a reliable transport network. Machine learning algorithms in other areas have demonstrated their ability to deal with uncertainties. They can be used for pattern recognition and more accurate prediction of demand. The classification, regression or detection of deviations are predictive tasks in the field of data mining [[TSK15](#)], that can be used in the field of transportation planning. An exemplary implementation of a machine learning approach, concretely reinforcement learning, has been presented in [section 7.2](#).

Seasonal changes, new restrictions, demand's development, variation of price, weather aspects or traffic patterns are variables affecting the planning of transport. They can be tracked, explored and analyzed in order to create a model, that is able to predict transport patterns and demand, thus helping decision tasks within the SND, like transport service's capacity.

One example for this is the great potential that still exists in the improvement of railway systems through the realization of predictive maintenance approaches. The low degree of digitalization has not yet permitted this sector to profit from deep analysis of processes and equipment utilization, but within the next years this will most likely change. As an example, the German government currently promotes several projects focusing on the digitalization of transport processes and infrastructure [BMV16] within the framework mFund (modernity funds). If the required data, like vehicle telematics, status, position, etc. is acquired and integrated, machine learning algorithms for pattern recognition and prediction can be implemented, similar as in a production environment [Jes+17b]. Doing so, the causes of faults can be identified before a possible failure occurs and system uncertainties within the transportation planning are reduced. All this leads to the realization of a more efficient planning and control of vehicles and routes, creating a more reliable and stable disposition of resources.

### **Data modeling and architecture for building common platforms**

Synchromodality can only become reality if an informed transport network with real-time data exists. In order to increase the adaptability and flexibility of the transport system and to minimize the reaction time when re-routing a shipment or vehicle for example, a fast and efficient data exchange between involved actors is required. Therefore the interoperability of relevant transport data systems must be guaranteed.

As seen in [subsection 3.3.2](#), the research activities in the construction of common communication and information platforms in logistic are still very small. Further research projects in cooperation with stakeholders, developing common data models, architectures and interfaces for a transparent and efficient data exchange are needed. Similar to the developments occurring in truck platooning presented in [section 7.3](#), the agreement of transport stakeholders for a common framework and communication protocols to share relevant standardized transport data is needed, enabling a real integration and cooperation of actors for creating a synchromodal network.

One example of a current project addressing this topic is the EU project SELIS [SEL16]. This project aims to developed a "platform that offers easy plug-and-play ways to share and analyse supply chain industry data in a neutral and privacy preserving manner, enabling the fulfillment of intelligent collaboration across the broader

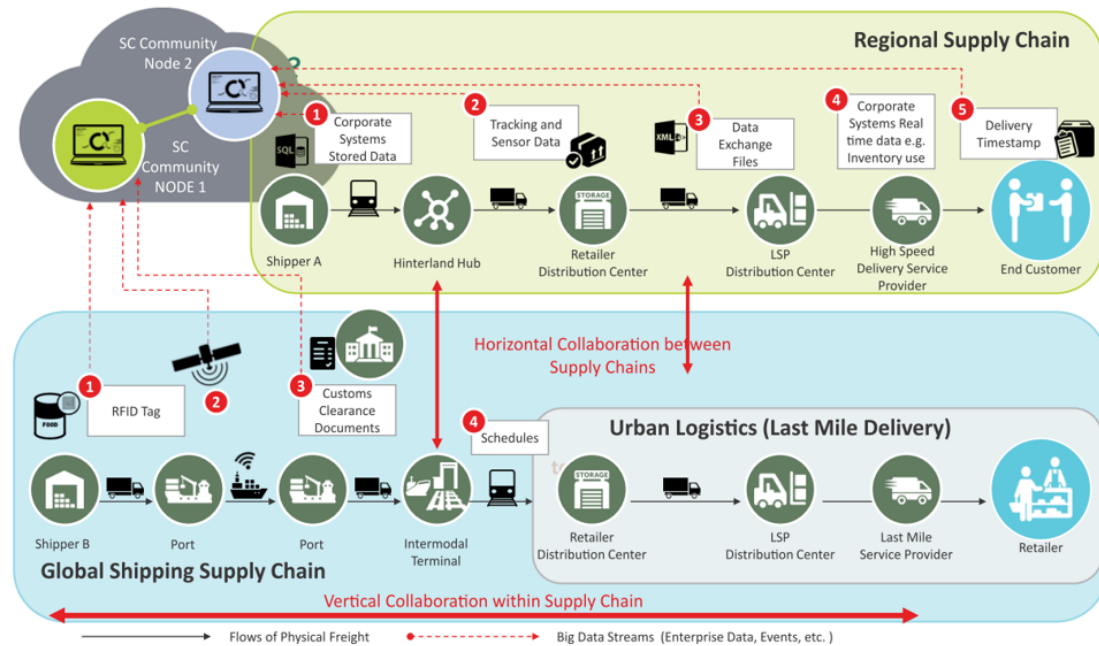


FIGURE 8.1: Supply chain community node concept [ERT18]

T&L [Transport and Logistic] sector" [ERT18]. Figure 8.1 presents the supply chain community that will be involved in the platform. Since the project just started, the time will show if their approach, possible from the theoretical side, will reach praxis.

Further research need for developing this kind of platforms should focus on powerful and scalable data architectures, which can work with a large amount of heterogeneous data e.g. by using semantic models for data description.

### Fairness models and regulatory framework in a cooperative environment

Since synchronodality requires a strong cooperation between transport actors, the development of fairness models for service payments and charges is crucial for the participation of all stakeholders. An agreement in terms of calculation of transport costs and service performance must be reached to increase synchronodality's acceptance among stakeholders.

Besides, the implementation of a booking procedure independent from the final transport operator delivering the transport service (free booking) raises liability questions that have to be solved, i.e. in case of cargo damage or delay. A common regulatory and legal framework for responsibility and liability of transport services and freight must be set. Given all these coordination processes, a new administrative infrastructure must be created for managing a synchronodal transport network.



## Appendix A

# Appendix - Intermodal costs calculation

Following figures present an exemplary calculation of the intermodal transport costs. The model returns an average value given in Euro/km per container transported (highlighted in green) for each transport mode for a transport carried out in Germany. The explanation of the selected values can be found in [section 4.4](#).

Hourly labour costs in Europa		
Country	Costs (€)	Index
EU	26,76	
Dänemark	42,48	125%
Belgien	39,65	116%
Schweden	38,33	112%
Luxemburg	37,58	110%
Frankreich	35,97	106%
Niederlande	34,77	102%
Deutschland	34,09	100%
Österreich	34,06	100%
Finnland	32,72	96%
Irland	30,97	91%
Italien	28,17	83%
Vereinigtes Königreich	25,68	75%
Spanien	21,17	62%
Slowenien	17,02	50%
Zypern	15,97	47%
Griechenland	14,52	43%
Portugal	14,10	41%
Malta	13,79	40%
Estland	11,74	34%
Tschechien	11,27	33%
Slowakei	11,07	32%
Kroatien	10,64	31%
Polen	9,36	27%
Ungarn	9,11	27%
Lettland	8,06	24%
Litauen	8,00	23%
Rumänien	6,33	19%
Bulgarien	4,93	14%

FIGURE A.1: Hourly labor costs from 2017 used for setting personal factor  $f_{Personal}$ . Data from [Eur18].

Cost Unit Road				
Procurement costs		Truck	Trailer	Cost per km per truck
	Unit			
Purchase price	€	100.000	23.000	
Residual value	%	10	10	
Mileage	km/year	100.000	100.000	
<b>Interest</b>				
Current assets	€	15.000	15.000	
Share of purchasing costs	%	50	50	
Working capital	€	65.000	26.500	
Interest rate	%	6,50%	6,50%	
<b>Depreciation costs</b>				
Service life	Year	6	12	
Depreciation	€/year	15.000	1.725	
<b>Tire costs</b>				
Mileage	km	150.000	150.000	
Number of tires		6	6	
Tire price	€	380	380	
Total tire costs	€/km	0,02	0,02	
<b>Maintenance and repair costs</b>				
Maintenance and repair	€/km	0,05	0,02	
<b>Insurance costs and taxes</b>				
Insurance	€/year	5.000	215	
Taxes	€/year	556		
<b>Operational costs without personnel and fuel</b>	€/km	<b>0,313</b>	<b>0,072</b>	⇒ 0,38 €/km
<b>Fuel and lubricant costs</b>				
Fuel consumption	l/100km	35		
Fuel price	€/l	1,14		
Fuel costs	€/km	0,40		
lubricant costs	€/km	0,01		
Total fuel and lubricant costs	€/km	0,41		⇒ 0,41 €/km
<b>Personnel costs</b>				
Driver's wage	€/Jahr	30.000		
Expenses	€/Jahr	3.000		
Factor personnel		1,3		
Employer's social security contribut	%	28		
Total Personnel costs	€/year	54.912		
Total personnel Costs per km	€/km	<b>0,55</b>		⇒ 0,55 €/km
Toll	€/km	<b>0,13</b>		
<b>Overhead and Margin</b>				
Overhead	%	<b>10%</b>		⇒ 1,65 €/km
Margin	%	<b>3%</b>		

FIGURE A.2: Parameters and exemplary values for the calculation of road transport costs adapted from [Lar15]

Cost Unit Rail			
Rolling stock	Unit	40 ISO cont. (16t payload)	
Locomotive			
Rent	€/day	2000	
Weight	t	83	
<b>Freight wagons</b>			
Type		Sgns 691	
Capacity	TEU	2	
Weight	t	20	
Rent	€/day	19	
Number of wagons		30	
Rental days	day	1	
Total freight wagons costs	€	570	
<b>Energy costs</b>			
Consumption	kWh/tkm	0,018	
Weight of locomotive and wagons	t	755	
Weight of freight	t	606	
Share of empty freight wagons		20%	
Total train weight	t	1216	
Consumption locomotive	kWh/km	21,89	
Price electricity (for industry in DE)	€/kWh	0,172	
Discount	%	5%	
Effective price electricity	€/kWh	0,1634	
Total energy costs	€/km	3,5765	
<b>Switching costs</b>			
Number of switching operations		2	
Total switching costs	€/operation	150	
<b>Overhead</b>			
Overhead	%	15%	
<b>Operational costs without personnel</b>	€/trainkm	<b>10,28</b>	<b>0,428</b> €/cont.km
<b>Personnel costs</b>			
Average distance per day	km	0	
Train operator's wage	€/h	50	
Travel time	h	9,00	
Train operator pre/post carriage	h	2,5	
Total personnel costs	€	575,00	
<b>Costs</b>	€/trainkm	<b>1,07</b>	<b>0,045</b> €/cont.km
<b>Train path price</b>			
Country price (DE - Reference)	€/trainkm	2,68	<b>0,112</b> €/cont.km
<b>Margin</b>			
Margin	%	5%	<b>0,614</b> €/cont.km

FIGURE A.3: Parameters and exemplary values for the calculation of rail transport costs adapted from [Lar15]

Train path charge 1.000 gross tonne freight train in 2014	
	€/Train-km
BE	2,37
SE	0,63
FR	1,60
DK	0,50
NL	2,46
AT	3,26
LU	0,86
DE	2,68
IT	2,45
ES	0,13
SI	1,00
PT	1,19
SK	2,75
CZ	3,39
HU	2,12
PL	3,00
CH	2,60
EU avg.	1,94

FIGURE A.4: Train path price for 1000 gross tonne freight train in 2014. Data from [Eura].

Cost Unit Barge			
	Unit	Type of barge	
		A: class Va (M9)	B: class Via (M12)
Capacity	TEU	272	398
Dimensions	m	135 x 11,4 x 3,5	135 x 17 x 4
Load capacity	t	3300	5000
Mode of operation		Continuous operation	Continuous operation
<b>Fixed Costs</b>			
Insurance	€/year	72.170	88.753
Maintenance and repair	€/year	34.466	36.297
Interest	€/year	81.890	115.667
Depreciation	€/year	254.717	352.325
Other costs	€/year	21.516	25.297
Port charge	€/year	24.493	35.692
Personnel costs	€/year	451.196	451.196
Total fixed costs	€/year	940.448	1.105.227
<b>Variable costs</b>			
Fuel consumption	l/km	12,1	16,3
Fuel price	€/l	0,62	0,62
Fuel costs	€/h	124,00	146,06
Total fuel costs	€	479.960	522.071
<b>Total costs</b>	€/year	1.420.408	1.627.298
<b>Total costs per hour</b>			
Operating hours	h/year	8064	8064
Total costs per hour	€/h	176,14	201,80
<b>Average driving parameter</b>			
Velocity	km/h	16,6	14,5
Driving hours	h/year	3.871	3.574
Annual mileage	km/year	64.254	51.828
<b>Costs</b>			
	€/TEUkm	0,0813	0,0789
<b>Cost adaption coefficient</b>			
40' PW Cont. - 2 TEU	€/cont.km	0,1625	0,1578
45' PW Cont. -2,25 TEU	€/cont.km	0,1829	0,1775

FIGURE A.5: Parameters and exemplary values for the calculation of waterway transport costs adapted from [Lar15]



## Appendix B

# Appendix - Python source code

## B.1 Implementation optimization algorithm

*This Appendix lists the relevant code which has been in [chapter 5](#).*

LISTING B.1: Method for creating transport network

```
def createNetwork(services_df):
network = nx.MultiDiGraph()
cities = list(set(list(services_df['start'])+list(services_df['end'])))
    ↪ )
network.add_nodes_from(cities)
for i in range(len(services_df)):
values = list(services_df.values[i])
network.add_edge(origin=values[0],destination=values[1],index=i,mode=
    ↪ values[2],air_distance=values[4])
return network
```

LISTING B.2: Method generating N shortest paths

```
def get_N_ShortestPaths(graph,source,target,N,max_length):
paths = list(set([tuple(path) for path in list(nx.all_simple_paths(
    ↪ graph, source, target, cutoff=max_length))]))
distances=[calculatePathTotalDistance(graph,list(zip(path,path[1:])))
    ↪ for path in paths]
N_smallest_distances_indexes = list(np.array(distances).argsort()[:N])
N_smallest_paths=[paths[index] for index in
    ↪ N_smallest_distances_indexes]
return N_smallest_paths
```

LISTING B.3: Method returning all the combinations of a set of edges

```
def getAllEdgesCombinations(edges):
return list(itertools.product(*edges))
```

LISTING B.4: Filtering of not feasible paths

```
def cleanPaths(services_df,paths,orders_df,order_index,stress_road,
    ↪ flexibility,teu_flexibility):
clean_paths = []
for path in paths:
if checkPathIntegrity(services_df,path):
if flexibility:
inTimeDelivery = checkTimeDelivery(services_df,path,orders_df,
    ↪ order_index,True)
else:
inTimeDelivery = checkTimeDelivery(services_df,path,orders_df,
    ↪ order_index,False)
if stress_road:
if inTimeDelivery:
clean_paths.append(path)
else:
teuAvailability = checkTeuAvailability(services_df,path,orders_df['teu
    ↪ '].loc[order_index],teu_flexibility)
if teuAvailability and inTimeDelivery:
clean_paths.append(path)
return clean_paths
```

LISTING B.5: Check in time delivery method

```
def checkTimeDelivery(services_df,path,orders_df,order_index,
    ↪ flexibility):
arrival=orders_df['ready_to_deliver'].loc[order_index].timestamp()
for service in path:
if services_df['mode'].loc[service] in ['Train','Barge']:
if(arrival<services_df['start_time'].loc[service].timestamp()):
arrival +=services_df['end_time'].loc[service].timestamp()
else:
return False
else: arrival+=dt.timedelta(minutes=int(services_df['duration'].loc[
    ↪ service])).total_seconds()
arrival=orders_df['ready_to_deliver'].loc[order_index].timestamp()
for service in path:
```

```

arrival=calculateServiceArrival(services_df,service,arrival)
if flexibility:
if(arrival<=orders_df['deliver_until'].loc[order_index].timestamp()):
return True
else:
return False3
else:
if(arrival<=orders_df['deliver_before'].loc[order_index].timestamp()):
return True
else:
return False

```

LISTING B.6: Check path capacity availability

```

def checkTeuAvailability(services_df,path,order_teu,teu_flexibility):
availability=True
for index in path:
if teu_flexibility:
if order_teu <=services_df['teu_flex'].loc[index]:
availability &= True
else: availability &= False
else:
if order_teu <=services_df['teu_available'].loc[index]:
availability &= True
else: availability &= False
return availability

```

## B.2 Implementation genetic optimization algorithms

### B.2.1 Single optimization algorithm

LISTING B.7: Random generation of first population

```

def generatePopulation(population_size):
population=[generateIndividual(nOrders) for i in range(population_size
↪ )]
return population

```

LISTING B.8: Generation of first population

```

def generateGoodIndividual(length,optimal_cost):
score= math.inf
test=0
while(score>1.05*optimal_cost and test<20):
individual = random.sample(range(length),length)
score = fitnessSingleObjective(individual)
test+=1
return individual

def generateSmartPopulation(population_size,optimal_cost):
population=[generateGoodIndividual(nOrders,optimal_cost) for i in tqdm
↪ (range(population_size))]
return population

```

LISTING B.9: Method calculating the result of the fitness function

```

def fitnessSingleObjective(sequence):
sequence_cost,num_assignments = calculateSequenceCostSingleObjective(
↪ sequence)
return sequence_cost*(len(sequence)-num_assignments+1)

```

LISTING B.10: Method for evaluating the population performance

```

def evaluateGeneration(population_performance):
return sum(population_performance)/len(population_performance)

```

LISTING B.11: Methods for parents selection

```

def selectParents(population,population_performance,nParents):
return [population[x] for x in list(np.array(population_performance).
↪ argsort()[ :nParents])]

def getBestParent(parents):
return parents[0]

```

LISTING B.12: Method for mutation operator 1

```

def mutateParents(parents,nMutations):
mutations=[shuffleList(parent[:i])+parent[i:] for parent in parents
↪ for i in range(2,nMutations+2)]
return mutations

```

LISTING B.13: Method for mutation operator 2

```
def mutateParents2(parents):
    mutations=[parent[:10*i+1]+shuffleList(parent[10*i+1:10*i+11])+parent
        ↪ [10*i+11:] for parent in parents for i in range(4)]
    return mutations
```

LISTING B.14: Method for mutation operator 3

```
def mutateParents3(parents):
    mutations=[parent[:5*i+1]+shuffleList(parent[5*i+1:5*i+6])+parent[5*i
        ↪ +6:] for parent in parents for i in range(8)]
    return mutations
```

## B.2.2 Multi-optimization algorithm - Implementation of NS-GAII

LISTING B.15: Implementation of NSGA in python code adapted from  
[DEA09]

```
#### Objects

IND_SIZE=42
POP_SIZE=20

creator.create("FitnessMin", base.Fitness, weights=(-1.0, -1.0))
creator.create("Individual", list, fitness=creator.FitnessMin)

toolbox = base.Toolbox()

#### Creators ####
toolbox = base.Toolbox()
toolbox.register("indices", random.sample, range(IND_SIZE), IND_SIZE)
toolbox.register("individual", tools.initIterate, creator.Individual,
    ↪ toolbox.indices)
toolbox.register("population", tools.initRepeat, list, toolbox.
    ↪ individual)

#### Operators ####
toolbox.register("evaluate", fitnessMultiObjective)
```

```

toolbox.register("mate1", tools.cxOrdered)
toolbox.register("mate2", tools.cxPartiallyMatched)
toolbox.register("mate3", tools.cxUniformPartiallyMatched, indpb=0.5)
toolbox.register("mutate", tools.mutShuffleIndexes, indpb=0.5)
toolbox.register("select", tools.selNSGA2)

NGEN = 10
MU = 100
CXPB = 0.9

stats = tools.Statistics(lambda ind: ind.fitness.values)
stats.register("min", numpy.min, axis=0)
stats.register("max", numpy.max, axis=0)

logbook = tools.Logbook()
logbook.header = "gen", "evals", "min", "max"

pop = toolbox.population(n=MU)

# Evaluate the individuals with an invalid fitness
invalid_ind = [ind for ind in pop if not ind.fitness.valid]
fitnesses = toolbox.map(toolbox.evaluate, invalid_ind)
for ind, fit in zip(invalid_ind, fitnesses):
    ind.fitness.values = fit

# To assign the crowding distance to the individuals, no actual
    ↔ selection is done
pop = toolbox.select(pop, len(pop))

record = stats.compile(pop)
logbook.record(gen=0, evals=len(invalid_ind), **record)
print(logbook.stream)
results={}

# Begin the generational process
for gen in range(1, NGEN):
    # Vary the population
    offspring = tools.selTournamentDCD(pop, len(pop))
    offspring = [toolbox.clone(ind) for ind in offspring]

```

```
for ind1, ind2 in zip(offspring[:,2], offspring[1::2]):
    if random.random() <= CXPB:
        toolbox.mate1(ind1, ind2)

        toolbox.mutate(ind1)
        toolbox.mutate(ind2)
        del ind1.fitness.values, ind2.fitness.values

# Evaluate the individuals with an invalid fitness
invalid_ind = [ind for ind in offspring if not ind.fitness.valid]
fitnesses = toolbox.map(toolbox.evaluate, invalid_ind)
for ind, fit in zip(invalid_ind, fitnesses):
    ind.fitness.values = fit

# Select the next generation population
pop = toolbox.select(pop+offspring,MU)
record = stats.compile(pop)
logbook.record(gen=gen, evals=len(pop), **record)
print(logbook.stream)

print("Final population hypervolume is %f" % hypervolume(pop))
```

## B.3 List of Python libraries

LISTING B.16: List of libraries for single objective optimization algorithms

```
import networkx as nx
import matplotlib.pyplot as plt
import pandas as pd
import warnings
import numpy as np
import itertools
import math
import time
import random
from tqdm import tqdm
import datetime as dt
```

```
import seaborn as sns
import logging
import re
import ast
```

LISTING B.17: List of libraries for genetic algorithm optimization

```
import random
from deap import base
from deap import creator
from deap import tools
```

# Appendix C

## Network data

Orders nr.	Origin	Destination	Nr. of TEU	Weight (t)	Time availability	Time to deliver	Time to deliver (flex)
1	Koeln	Rotterdam	4	64	07.05.2018 10:00	11.05.2018 12:00	11.05.2018 12:00
2	Koeln	Rotterdam	1	16	10.05.2018 00:00	11.05.2018 12:00	11.05.2018 22:00
3	Koeln	Rotterdam	2	32	08.05.2018 05:00	10.05.2018 00:00	10.05.2018 19:00
4	Neuss	Hamburg	6	96	07.05.2018 12:00	11.05.2018 12:00	11.05.2018 12:00
5	Koeln	Hamburg	3	48	07.05.2018 11:00	11.05.2018 12:00	11.05.2018 12:00
6	Dortmund	Antwerpen	5	80	07.05.2018 10:30	11.05.2018 12:00	11.05.2018 12:00
7	Duesseldorf	Hamburg	2	32	07.05.2018 14:00	11.05.2018 12:00	11.05.2018 12:00
8	Duesseldorf	Antwerpen	4	64	07.05.2018 16:00	11.05.2018 12:00	11.05.2018 12:00
9	Koeln	Rotterdam	3	48	08.05.2018 10:00	11.05.2018 12:00	11.05.2018 12:00
10	Koeln	Rotterdam	1	16	07.05.2018 12:00	11.05.2018 12:00	11.05.2018 12:00
11	Koeln	Rotterdam	2	32	09.05.2018 10:00	11.05.2018 12:00	11.05.2018 12:00
12	Koeln	Rotterdam	3	48	08.05.2018 12:00	11.05.2018 12:00	11.05.2018 12:00
13	Neuss	Hamburg	2	32	07.05.2018 14:30	11.05.2018 12:00	11.05.2018 12:00
14	Neuss	Hamburg	2	32	08.05.2018 16:00	11.05.2018 12:00	11.05.2018 12:00
15	Neuss	Hamburg	1	16	09.05.2018 10:00	11.05.2018 12:00	11.05.2018 12:00
16	Neuss	Hamburg	4	64	08.05.2018 12:00	11.05.2018 12:00	11.05.2018 12:00
17	Neuss	Hamburg	1	16	10.05.2018 00:30	11.05.2018 16:00	11.05.2018 23:45
18	Neuss	Hamburg	2	32	08.05.2018 00:00	10.05.2018 17:00	10.05.2018 20:00
19	Koeln	Hamburg	3	48	07.05.2018 16:00	11.05.2018 12:00	11.05.2018 12:00
20	Koeln	Hamburg	2	32	08.05.2018 10:00	11.05.2018 12:00	11.05.2018 12:00
21	Koeln	Hamburg	1	16	09.05.2018 08:00	11.05.2018 12:00	11.05.2018 12:00
22	Koeln	Hamburg	3	48	08.05.2018 14:00	11.05.2018 12:00	11.05.2018 12:00
23	Koeln	Hamburg	1	16	10.05.2018 01:00	11.05.2018 21:00	11.05.2018 23:30
24	Koeln	Hamburg	2	32	08.05.2018 01:00	09.05.2018 22:00	09.05.2018 23:00
25	Dortmund	Antwerpen	2	32	07.05.2018 18:00	11.05.2018 12:00	11.05.2018 12:00
26	Dortmund	Antwerpen	1	16	08.05.2018 12:00	11.05.2018 12:00	11.05.2018 12:00
27	Dortmund	Antwerpen	3	48	09.05.2018 06:00	11.05.2018 12:00	11.05.2018 12:00
28	Dortmund	Antwerpen	2	32	08.05.2018 20:00	11.05.2018 12:00	11.05.2018 12:00
29	Dortmund	Antwerpen	2	32	10.05.2018 02:00	11.05.2018 22:00	12.05.2018 09:00
30	Dortmund	Antwerpen	1	16	07.05.2018 00:00	09.05.2018 12:00	09.05.2018 21:00
31	Duesseldorf	Hamburg	2	32	07.05.2018 08:00	11.05.2018 12:00	11.05.2018 12:00
32	Duesseldorf	Hamburg	1	16	08.05.2018 13:00	11.05.2018 12:00	11.05.2018 12:00
33	Duesseldorf	Hamburg	3	48	09.05.2018 02:00	11.05.2018 12:00	11.05.2018 12:00
34	Duesseldorf	Hamburg	2	32	08.05.2018 20:00	11.05.2018 12:00	11.05.2018 12:00
35	Duesseldorf	Hamburg	1	16	08.05.2018 22:00	11.05.2018 17:00	11.05.2018 23:00
36	Duesseldorf	Hamburg	2	32	10.05.2018 02:00	11.05.2018 18:00	11.05.2018 21:00
37	Duesseldorf	Antwerpen	1	16	07.05.2018 12:50	11.05.2018 12:00	11.05.2018 12:00
38	Duesseldorf	Antwerpen	4	64	08.05.2018 14:00	11.05.2018 12:00	11.05.2018 12:00
39	Duesseldorf	Antwerpen	3	48	09.05.2018 00:00	11.05.2018 12:00	11.05.2018 12:00
40	Duesseldorf	Antwerpen	2	32	08.05.2018 10:50	11.05.2018 12:00	11.05.2018 12:00
41	Duesseldorf	Antwerpen	3	48	07.05.2018 06:00	10.05.2018 10:00	10.05.2018 15:00
42	Duesseldorf	Antwerpen	2	32	10.05.2018 00:50	11.05.2018 19:30	11.05.2018 23:30

FIGURE C.1: Table containing orders used for results

Nr.	T. start	T. end	Mode	Distance	Capacity available	Capacity flexibility	Start time	End time
1	Dortmund	Hamburg	Train	284	10	20	09.05.2018 12:30	11.05.2018 00:00
2	Dortmund	Hamburg	Train	284	10	20	10.05.2018 12:30	11.05.2018 23:30
3	Dortmund	Hamburg	Train	284	10	20	11.05.2018 12:30	13.05.2018 03:00
4	Dortmund	Hamburg	Truck	284	10	20	on_time	on_time
5	Duisburg	Hamburg	Train	322	10	20	08.05.2018 19:25	10.05.2018 00:00
6	Duisburg	Hamburg	Train	322	10	20	09.05.2018 19:25	11.05.2018 00:00
7	Duisburg	Hamburg	Truck	322	10	20	on_time	on_time
8	Duisburg	Dortmund	Train	50	10	20	07.05.2018 19:25	08.05.2018 05:20
9	Duisburg	Dortmund	Train	50	10	20	08.05.2018 19:25	10.05.2018 07:35
10	Duisburg	Dortmund	Truck	50	10	20	on_time	on_time
11	Duesseldorf	Dortmund	Train	58	10	20	07.05.2018 11:25	09.05.2018 07:35
12	Duesseldorf	Dortmund	Train	58	10	20	08.05.2018 11:25	10.05.2018 07:35
13	Duesseldorf	Dortmund	Train	58	10	20	09.05.2018 15:20	11.05.2018 07:35
14	Duesseldorf	Dortmund	Truck	58	10	20	on_time	on_time
15	Koeln	Dortmund	Train	73	10	20	07.05.2018 12:00	09.05.2018 07:35
16	Koeln	Dortmund	Truck	73	10	20	on_time	on_time
17	Koeln	Antwerpen	Truck	182	10	20	on_time	on_time
18	Koeln	Neuss	Train	26	10	20	07.05.2018 12:00	08.05.2018 08:10
19	Koeln	Neuss	Truck	26	10	20	on_time	on_time
20	Koeln	Duesseldorf	Train	35	10	20	07.05.2018 12:00	08.05.2018 10:00
21	Koeln	Duesseldorf	Truck	35	10	20	on_time	on_time
22	Koeln	Duisburg	Train	57	10	20	07.05.2018 12:00	09.05.2018 07:00
23	Koeln	Duisburg	Truck	57	10	20	on_time	on_time
24	Neuss	Duesseldorf	Train	9	10	20	07.05.2018 15:00	08.05.2018 10:00
25	Neuss	Duesseldorf	Train	9	10	20	08.05.2018 17:05	09.05.2018 10:05
26	Neuss	Duesseldorf	Truck	9	10	20	on_time	on_time
27	Duesseldorf	Duisburg	Train	23	10	20	07.05.2018 11:25	08.05.2018 07:10
28	Duesseldorf	Duisburg	Train	23	10	20	08.05.2018 11:25	09.05.2018 07:10
29	Duesseldorf	Duisburg	Truck	23	10	20	on_time	on_time
30	Neuss	Duisburg	Train	32	10	20	07.05.2018 17:05	08.05.2018 15:00
31	Neuss	Duisburg	Train	32	10	20	08.05.2018 17:05	10.05.2018 07:00
32	Neuss	Duisburg	Truck	32	10	20	on_time	on_time
33	Neuss	Antwerpen	Truck	166	10	20	on_time	on_time
34	Duisburg	Antwerpen	Truck	166	10	20	on_time	on_time
35	Antwerpen	Rotterdam	Train	79	10	20		
36	Antwerpen	Rotterdam	Truck	79	10	20	on_time	on_time
37	Antwerpen	Rotterdam	Barge	79	10	20	08.05.2018 21:00	09.05.2018 20:00
38	Neuss	Rotterdam	Train	181	10	20	08.05.2018 17:05	10.05.2018 09:45
39	Neuss	Rotterdam	Truck	181	10	20	on_time	on_time
40	Duesseldorf	Rotterdam	Train	177	10	20	09.05.2018 16:15	10.05.2018 23:50
41	Duesseldorf	Rotterdam	Truck	177	10	20	on_time	on_time
42	Duisburg	Rotterdam	Train	167	10	20		
43	Duisburg	Rotterdam	Truck	167	10	20	on_time	on_time
44	Dortmund	Rotterdam	Train	211	10	20		
45	Dortmund	Rotterdam	Truck	211	10	20	on_time	on_time

FIGURE C.2: Table containing services used for results

Nr.	Costs	Environ. Costs	Transshipment costs	Transshipment env. Costs	Transshipment duration
1	200,391962	179,769728	20	35,3914	60
2	200,391962	179,769728	20	35,3914	60
3	200,391962	179,769728	20	35,3914	60
4	538,89	756,07616	0	0	0
5	227,204971	203,823424	20	35,3914	60
6	227,204971	203,823424	20	35,3914	60
7	610,995	857,24128	0	0	0
8	35,280275	31,6496	20	35,3914	60
9	35,280275	31,6496	20	35,3914	60
10	94,875	133,112	0	0	0
11	40,925119	36,713536	20	35,3914	60
12	40,925119	36,713536	20	35,3914	60
13	40,925119	36,713536	20	35,3914	60
14	110,055	154,40992	0	0	0
15	51,5092015	46,208416	20	35,3914	60
16	138,5175	194,34352	0	0	0
17	345,345	484,52768	0	0	0
18	18,345743	16,457792	20	35,3914	60
19	49,335	69,21824	0	0	0
20	24,6961925	22,15472	20	35,3914	60
21	66,4125	93,1784	0	0	0
22	40,2195135	36,080544	20	35,3914	60
23	108,1575	151,74768	0	0	0
24	6,3504495	5,696928	20	35,3914	60
25	6,3504495	5,696928	20	35,3914	60
26	17,0775	23,96016	0	0	0
27	16,2289265	14,558816	20	35,3914	60
28	16,2289265	14,558816	20	35,3914	60
29	43,6425	61,23152	0	0	0
30	22,579376	20,255744	20	35,3914	60
31	22,579376	20,255744	20	35,3914	60
32	60,72	85,19168	0	0	0
33	314,985	441,93184	0	0	0
34	314,985	441,93184	0	0	0
35	55,7428345	50,006368	20	35,3914	60
36	149,9025	210,31696	0	0	0
37	16,616465	57,989792	30	35,3914	30
38	127,714596	114,571552	20	35,3914	60
39	343,4475	481,86544	0	0	0
40	124,892174	112,039584	20	35,3914	60
41	335,8575	471,21648	0	0	0
42	117,836119	105,709664	20	35,3914	60
43	316,8825	444,59408	0	0	0
44	148,882761	133,561312	20	35,3914	60
45	400,3725	561,73264	0	0	0

FIGURE C.3: Table containing services used for results

Nr.	T. start	T. end	Mode	Distance	Capacity available	Capacity flexibility	Start time	End time
46	Duisburg	Antwerpen	Barge	166	10	20	08.05.2018 21:00	09.05.2018 20:00
47	Duisburg	Rotterdam	Barge	166	10	20	09.05.2018 19:25	10.05.2018 20:00
48	Neuss	Antwerpen	Barge	337	10	20	08.05.2018 21:00	09.05.2018 20:00
49	Neuss	Rotterdam	Barge	276	10	20	09.05.2018 19:25	10.05.2018 20:00
50	Dortmund	Duesseldorf	Truck	58	10	20	on_time	on_time
51	Dortmund	Duesseldorf	Train	58	10	20	07.05.2018 13:40	08.05.2018 07:00
52	Dortmund	Duesseldorf	Train	58	10	20	07.05.2018 19:00	08.05.2018 18:15
53	Dortmund	Duesseldorf	Train	58	10	20	08.05.2018 00:35	09.05.2018 08:15
54	Dortmund	Duisburg	Truck	50	10	20	07.05.2018 13:40	08.05.2018 07:00
55	Dortmund	Duisburg	Train	50	10	20	07.05.2018 13:40	08.05.2018 07:00
56	Dortmund	Duisburg	Train	50	10	20	07.05.2018 19:00	08.05.2018 07:00
57	Dortmund	Duisburg	Train	50	10	20	08.05.2018 00:35	09.05.2018 07:00
58	Duesseldorf	Neuss	Truck	9	10	20	07.05.2018 16:15	08.05.2018 08:10
59	Duesseldorf	Neuss	Train	9	10	20	07.05.2018 16:15	08.05.2018 08:10
60	Duesseldorf	Neuss	Train	9	10	20	08.05.2018 16:15	09.05.2018 08:10
61	Duesseldorf	Neuss	Train	9	10	20	09.05.2018 16:15	10.05.2018 08:10
62	Duisburg	Duesseldorf	Truck	23	10	20	on_time	on_time
63	Duisburg	Duesseldorf	Train	23	10	20	07.05.2018 19:25	08.05.2018 07:00
64	Duisburg	Duesseldorf	Train	23	10	20	08.05.2018 16:15	09.05.2018 07:00
65	Duisburg	Duesseldorf	Train	23	10	20	09.05.2018 16:15	10.05.2018 07:00
66	Duisburg	Neuss	Truck	32	10	20	on_time	on_time
67	Duisburg	Neuss	Train	32	10	20	07.05.2018 19:25	09.05.2018 03:30
68	Duisburg	Neuss	Train	32	10	20	08.05.2018 16:15	10.05.2018 03:30
69	Duisburg	Neuss	Train	32	10	20	09.05.2018 16:15	11.05.2018 03:30
70	Dortmund	Koeln	Truck	73	10	20	on_time	on_time
71	Dortmund	Koeln	Train	73	10	20	07.05.2018 13:45	08.05.2018 20:50
72	Dortmund	Koeln	Train	73	10	20	08.05.2018 13:45	09.05.2018 20:50
73	Dortmund	Koeln	Train	73	10	20	09.05.2018 13:45	10.05.2018 20:50
74	Duesseldorf	Koeln	Truck	35	10	20	on_time	on_time
75	Duesseldorf	Koeln	Train	35	10	20	07.05.2018 16:15	08.05.2018 04:00
76	Duesseldorf	Koeln	Train	35	10	20	08.05.2018 16:15	09.05.2018 04:00
77	Duesseldorf	Koeln	Train	35	10	20	09.05.2018 16:15	10.05.2018 04:00
78	Duesseldorf	Koeln	Train	35	10	20	10.05.2018 16:15	11.05.2018 04:00
79	Neuss	Koeln	Truck	26	10	20	on_time	on_time
80	Neuss	Koeln	Train	26	10	20	07.05.2018 17:05	08.05.2018 02:55
81	Neuss	Koeln	Train	26	10	20	08.05.2018 17:05	09.05.2018 02:55
82	Neuss	Koeln	Train	26	10	20	09.05.2018 17:05	10.05.2018 02:55
83	Neuss	Koeln	Train	26	10	20	10.05.2018 17:05	11.05.2018 02:55
84	Duisburg	Antwerpen	Train	166	10	20	07.05.2018 19:25	08.05.2018 20:00
85	Duisburg	Antwerpen	Train	166	10	20	07.05.2018 19:25	08.05.2018 20:00
86	Duisburg	Antwerpen	Train	166	10	20	07.05.2018 19:25	08.05.2018 20:00
87	Neuss	Antwerpen	Train	166	10	20	07.05.2018 17:05	08.05.2018 08:00
88	Neuss	Antwerpen	Train	166	10	20	08.05.2018 17:05	09.05.2018 08:00
89	Neuss	Antwerpen	Train	166	10	20	09.05.2018 17:05	10.05.2018 08:00
90	Neuss	Antwerpen	Train	166	10	20	10.05.2018 17:05	11.05.2018 08:00
91	Koeln	Antwerpen	Train	182	10	20	07.05.2018 16:00	08.05.2018 08:00
92	Koeln	Antwerpen	Train	182	10	20	08.05.2018 16:00	09.05.2018 08:00
93	Koeln	Antwerpen	Train	182	10	20	09.05.2018 16:00	10.05.2018 08:00
94	Koeln	Antwerpen	Train	182	10	20	10.05.2018 16:00	11.05.2018 08:00

FIGURE C.4: Table containing services used for results

Nr.	Costs	Environ. Costs	Transshipment costs	Transshipment env. Costs	Transshipment duration
46	34,91561	121,851968	30	35,3914	60
47	34,91561	121,851968	30	35,3914	60
48	70,882895	247,374176	30	35,3914	60
49	58,05246	202,597248	30	35,3914	60
50	110,055	154,40992	0	0	0
51	40,925119	36,713536	20	35,3914	60
52	40,925119	36,713536	20	35,3914	60
53	40,925119	36,713536	20	35,3914	60
54	94,875	133,112	0	0	0
55	35,280275	31,6496	20	35,3914	60
56	35,280275	31,6496	20	35,3914	60
57	35,280275	31,6496	20	35,3914	60
58	17,0775	23,96016	20	35,3914	60
59	6,3504495	5,696928	20	35,3914	60
60	6,3504495	5,696928	20	35,3914	60
61	6,3504495	5,696928	20	35,3914	60
62	43,6425	61,23152	0	0	0
63	16,2289265	14,558816	20	35,3914	60
64	16,2289265	14,558816	20	35,3914	60
65	16,2289265	14,558816	20	35,3914	60
66	60,72	85,19168	0	0	0
67	22,579376	20,255744	20	35,3914	60
68	22,579376	20,255744	20	35,3914	60
69	22,579376	20,255744	20	35,3914	60
70	138,5175	194,34352	0	0	0
71	51,5092015	46,208416	20	35,3914	60
72	51,5092015	46,208416	20	35,3914	60
73	51,5092015	46,208416	20	35,3914	60
74	66,4125	93,1784	0	0	0
75	24,6961925	22,15472	20	35,3914	60
76	24,6961925	22,15472	20	35,3914	60
77	24,6961925	22,15472	20	35,3914	60
78	24,6961925	22,15472	20	35,3914	60
79	49,335	69,21824	0	0	0
80	18,345743	16,457792	20	35,3914	60
81	18,345743	16,457792	20	35,3914	60
82	18,345743	16,457792	20	35,3914	60
83	18,345743	16,457792	20	35,3914	60
84	117,130513	105,076672	20	35,3914	60
85	117,130513	105,076672	20	35,3914	60
86	117,130513	105,076672	20	35,3914	60
87	117,130513	105,076672	20	35,3914	60
88	117,130513	105,076672	20	35,3914	60
89	117,130513	105,076672	20	35,3914	60
90	117,130513	105,076672	20	35,3914	60
91	128,420201	115,204544	20	35,3914	60
92	128,420201	115,204544	20	35,3914	60
93	128,420201	115,204544	20	35,3914	60
94	128,420201	115,204544	20	35,3914	60

FIGURE C.5: Table containing services used for results

	assigned	teu	monetary_cost	impact_cost	sr1_ind	sr1_mode	sr1_dist	sr1_t/km	sr2_ind	sr2_mode	sr2_dist	sr2_t/km	sr3_ind	sr3_mode	sr3_dist	sr3_t/km	avg_train_t/km	avg_truck_t/km	avg_barge_t/km	
20	WAHR	4	425,592812	101,778576	17	Train	26	1664	48	Barge	276	17664					1664	0	17664	
5	WAHR	1	402,27	56,439488	20	Truck	35	560	40	Truck	177	2832					0	1696	0	
17	WAHR	2	785,565	110,216736	18	Truck	26	832	38	Truck	181	5792					0	3312	0	
2	WAHR	6	1618,706082	155,6823408	29	Train	32	3072	4	Train	322	30912					16992	0	0	
41	WAHR	3	815,7034905	78,4108632	14	Train	73	3504	0	Train	284	13632					8568	0	0	
3	WAHR	5	500,979425	94,446484	54	Train	50	4000	45	Barge	166	13280					4000	0	13280	
24	WAHR	2	526,867795	50,754728	27	Train	23	736	5	Train	322	10304					5520	0	0	
6	WAHR	4	428,933378	115,3850016	58	Train	9	576	47	Barge	337	21568					576	0	21568	
11	WAHR	3	412,16238	92,1620664	18	Truck	26	1248	48	Barge	276	13248					0	1248	13248	
36	WAHR	1	211,3046735	24,0609384	20	Truck	35	560	39	Train	177	2832					2832	560	0	
0	WAHR	2	422,609347	48,1218768	18	Truck	26	832	25	Truck	9	288		39	Train	177	5664	560	0	
27	WAHR	3	412,16238	92,1620664	18	Truck	26	1248	48	Barge	276	13248					0	1248	13248	
8	WAHR	2	539,568694	51,8941136	29	Train	32	1024	4	Train	322	10304					5664	0	0	
18	WAHR	2	594,395841	61,2286544	24	Train	9	288	28	Truck	23	736		5	Train	322	10304	5296	736	0
10	WAHR	1	307,924971	32,4406504	25	Truck	9	144	28	Truck	23	368		5	Train	322	5152	256	0	
12	WAHR	4	2534,297504	350,9988096	30	Train	32	2048	6	Truck	322	20608					2048	20608	0	
13	WAHR	1	666,0225	93,444624	25	Truck	9	144	13	Truck	58	928		3	Truck	284	4544	1872	0	
1	WAHR	2	615,849942	64,8813008	25	Truck	9	288	28	Truck	23	736		4	Train	322	10304	512	0	
14	WAHR	3	1066,087413	117,2887512	22	Truck	57	2736	5	Train	322	15456					15456	2736	0	
21	WAHR	2	717,818924	81,9009296	15	Truck	73	2336	0	Train	284	9088					9088	2336	0	
39	WAHR	1	355,362471	39,0962504	22	Truck	57	912	5	Train	322	5152					5152	912	0	
19	WAHR	3	1076,728386	122,8513944	15	Truck	73	3504	0	Train	284	13632					13632	3504	0	
26	WAHR	1	677,4075	95,041968	15	Truck	73	1168	3	Truck	284	4544					0	2856	0	
7	WAHR	2	1354,815	190,083936	15	Truck	73	2336	3	Truck	284	9088					0	5712	0	
9	WAHR	2	200,39177	37,7785936	55	Train	50	1600	45	Barge	166	5312					1600	0	5312	
4	WAHR	1	159,79061	29,0355368	53	Truck	50	800	45	Barge	166	2656					0	800	2656	
28	WAHR	3	792,789039	95,6514456	49	Truck	58	2784	57	Truck	9	432					7968	1608	0	
30	WAHR	2	319,58122	58,0710736	53	Truck	50	1600	45	Barge	166	5312					0	1600	5312	
23	WAHR	2	528,526026	63,676304	49	Truck	58	1856	57	Truck	9	288		89	Train	166	5312	1072	0	
33	WAHR	1	195,133132	20,1141768	50	Train	58	928	57	Truck	9	144		87	Train	166	2656	144	0	
29	WAHR	2	522,634162	50,3749328	10	Train	58	1856	0	Train	284	9088					5472	0	0	
16	WAHR	1	579,815119	79,2789696	12	Train	58	928	3	Truck	284	4544					928	4544	0	
38	WAHR	3	1739,445357	237,8369088	12	Train	58	2784	3	Truck	284	13632					2784	13632	0	
22	WAHR	2	1159,630238	158,5579392	12	Train	58	1856	3	Truck	284	9088					1856	9088	0	
32	WAHR	1	290,84771	30,0446344	28	Truck	23	368	5	Train	322	5152					5152	368	0	
35	WAHR	2	1309,275	183,69456	28	Truck	23	736	6	Truck	322	10304					0	5520	0	
34	WAHR	1	107,2333445	28,8462504	58	Train	9	144	47	Barge	337	5392					144	0	5392	
15	WAHR	4	573,92385	58,466	59	Train	9	576	88	Train	166	10624					5600	0	0	
25	WAHR	3	430,4428875	43,8495	60	Train	9	432	89	Train	166	7968					4200	0	0	
40	WAHR	2	235,92079	61,3451472	57	Truck	9	288	47	Barge	337	10784					0	288	10784	0
31	WAHR	3	321,7000335	86,5387512	58	Train	9	432	47	Barge	337	16176					432	288	16176	0
37	WAHR	2	308,416026	32,8856464	57	Truck	9	288	89	Train	166	5312					5312	288	0	

FIGURE C.6: Results of orders' assignments calculated by the created Random GA optimization model

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