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Optimization and Simulation of Platform Supply Pickup and Delivery

Case from the Brazilian Petroleum Industry

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- uttak av masteroppgave

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Oppgavetekst/Problembeskrivelse The aim of this thesis is building a tool for exploring different approaches to optimize the supply pickup and delivery to platforms in the Brazilian petroleum industry. This includes taking elements like delays, no-shows and overbooking into account. In doing so, the current routes used when servicing platforms are challenged, and new methods and models are developed. Main contents: 1. Describing the problem. 2. Developing mathematical models for the problem at hand 3. Describing and implementing solution methods for the models using the commercial software Xpress/Mosel 4. Performing a computational study where the solution methods are tested with relevant data. 5. Discussing the results and the applicability of the models and solution methods.	
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Abstract

The oil industry has a vital role in energy provision and the economic aspects of its operations, which is associated with high values and risks. Continuous oil production from fields is essential, and it is important that this is supported by robust logistics solutions. Offshore production facilities require supplies that are transported from an onshore port to the facility by platform supply vessels. Ship transportation is the most costly part of the upstream logistics sector, making good planning even more critical. This study examines the order cycle for Petrobras in the Campos Basin in Brazil. Models are developed simulating the situations where supply orders are generated from a random distribution and where different policies concerning the vessel voyages are applied. Periodic problems are solved to determine the order service and corresponding sailing routes for each given ship journey.

The objective functions minimises costs for orders that are not served at departures from where they are requested, in addition to the distances travelled when this is proposed as a possibility. Inconvenience costs were set proportional to the demand quantities for the specific orders, with more weight put on delivery service rather than pickup. The model is flexible and simple with fixed routes and schedules in use, imitating the present situation. Challenging the voyages however, complicates it.

Petrobras experience problems in their supply chain originating in onshore logistics. 25 % of the orders scheduled for given departures arrive at the port too late to be transported, and 50 % of orders are requested as emergencies whilst the percentage in fact should be 10. No-shows lead to low utilisation of the vessels and frequent express leasing, which if further impacted by the amount of emergencies in need of hurried services with express. Overbooking is a strategy that potentially can correct parts of the problem. This was proven when planning for 20-25 % excess capacity than the actual, where the expected delays were reduced by one third. If Petrobras were able to reduce the proportion of no-shows to 15 % and emergency requests back to its normal state of 10 %, the analyses show reductions of nearly 40 % and 80 % in order delay and express demand, respectively. In addition, if they were able to make their Logistics compatible with dynamic route planning as well, the potential of saving up to 70-75 % in order delay is evident, where there no longer exists any reasons to use express. This should act as an incentive to make an effort to improve the logistics system. Nevertheless, there is a trade-off with the use of different policies applied due to the uncertain nature of the problem. A detailed evaluation is left to the decision makers.

Preface

This paper represents the author's dissertation for the degree of Master of Science in Industrial Economics and Technology Management at the Norwegian University of Science and Technology (NTNU). It is the result of the thesis work for the course TIØ4905, which is the final assignment of the academic program for students choosing the specialisation Managerial Economics and Operations Research. The work performed is a continuation of a specialization project completed in the autumn of 2013 (Gausel and Hagen, 2013).

The purpose of the master thesis has been to develop a general tool for logistics planning related to the delivery of supplies for oil platforms offshore. It is applied to simulated scenarios for Petrobras, using realistic data inputs to represent the ordering cycle and the interplay between supply chain participants. Different policies were challenged, where alternative methods and solution were tested to see their implications on the present situation. A basis for the topic was provided by NTNU and the Center for Integrated Operations (IO Center), and further shaped according to the findings made throughout the study.

With regard to guidance and feedback for the duration of the last year, I would like to thank my academic supervisors Professor Kjetil Fagerholt and Associate Professor Henrik Andersson. Your help has meant a lot to me. I also want to direct my gratitude towards Research Scientist Even Ambros Holte at MARINTEK and PhD Candidate Eirik Fernández Cuesta for their insights and valuable input.

Lastly, I would like to thank my family and friends for your unconditional support and understanding. In particular, I am grateful for my sister's encouragement. Thank you for always being there and listening whenever needed.

Lillestrøm 19.09.14

Martine Rambøl Hagen

Table of contents

List of Tables

List of Figures

Chapter 1

Introduction

Oil and gas supply the majority of the energy needed globally, where one third of the global energy consumption is supplied by oil alone. The oil and gas industry is associated with very large monetary values, comprising highly advanced technology and costly operations. It is divided in two main sectors: upstream and downstream. The upstream sector includes exploration and production of hydrocarbons, while downstream concerns refining, distribution and retailing. This thesis focuses on logistics in the upstream segment of the industry, which is defined as supplying the offshore drilling and production units with all necessary goods (Aas, 2009). Figure 1-1 shows an overview of the entire petroleum supply chain. One of the largest companies operating in this sector is the Brazilian integrated energy corporation Petróleo Brasileiro S.A., also known as Petrobras.

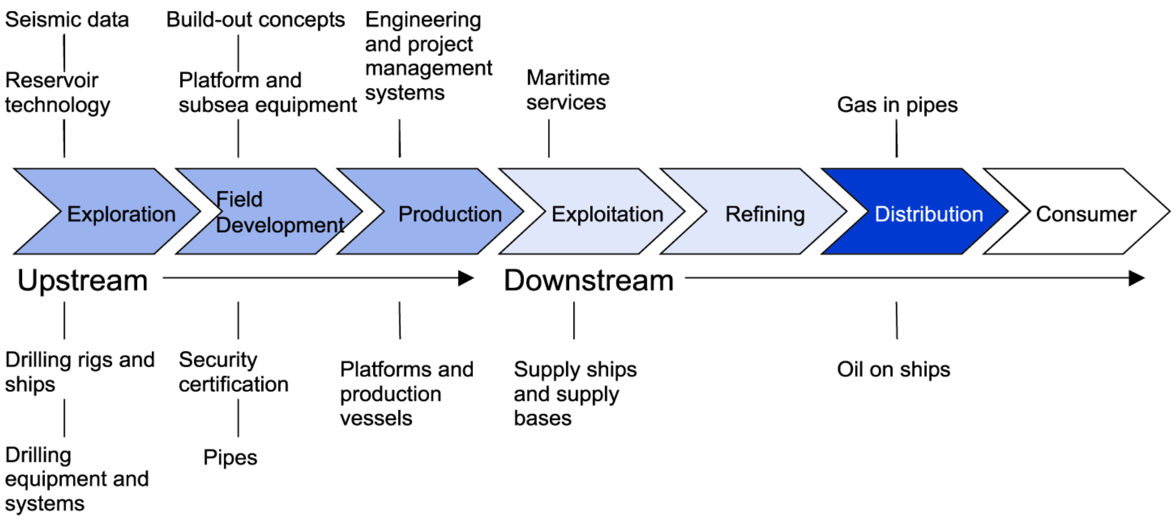

Figure 1-1: *The petroleum supply chain (Friedberg, 2012b)*

The present study is geographically limited to Brazil, specifically the fields owned and operated by Petrobras outside the coast in the southeast of the country. Petrobras is the main state owned oil company in Brazil, representing approximately 96% of the Brazilian oil and gas production. They are currently expanding their reservoirs after recent discoveries outside the Brazilian coast, which contains billions of barrels of oil. The reserves are at present estimated containing up to 12.3 billion recoverable barrels of oil equivalents (boe) (Guedes, 2013). This can potentially transform Brazil into one of the leading oil producers and exporters in the world. To meet this Petrobras are planning to double their production of hydrocarbons from the Brazilian shelf within 2020.

For Petrobras to reach their goals, significant challenges need to be overcome. The new findings exceed 300 km from the Brazilian coast, making the new discoveries more difficult to reach than before (Guedes, 2013). In addition, the new oil findings are trapped under some additional 1000 meters of rock and 2000 meters of compressed salt compared to the past findings of a maximum of 4000 meters below sea level (Aas, 2012). Some estimates put the total required supply chain investment at USD 1 trillion, emphasising the tremendous amount of money and thus the potential for saving large sums with optimal planning (Friedberg, 2013).

Petrobras operate offshore installations that are in need of regular supplies of commodities from the mainland. The focus here is on the transportation of such supplies. Production facilities are used at offshore sites, and include traditional production platforms as well as floating production storage and offloading units (FPSOs). These facilities place requests to the port for supplies, either to be delivered or picked up. There are several types of offshore installations representing different logistical needs. The size can vary from small, unmanned units to large constructions in which several hundred workers are placed. Consequently, the need for supplies to support daily operations and the amount of equipment needed will vary significantly (Aas, 2009). Platform supply vessels (PSVs) serve these supply requests, transporting cargo from the port and to a set of platforms and back to the port. It is essential to meet the demands in order to ensure continuous production of petroleum. Most oil companies charter PSVs on the market. The cost of chartering and operating PSVs is among the largest upstream logistic costs, so it is vital to minimise the rate and maximise utilisation (Aas et al., 2009).

Following this, the purpose of this thesis is to examine the logistics system at Petrobras, with the intention to uncover potential cost saving areas that can be significant for the future. A new method is needed to improve the integrated logistics system, and the main objective is to find such a method and make use of it to see its implications for existing challenges within the frame of Petrobras' current operations. With this in mind, the aim is to develop a practical tool for logistics planning and to make use of it when analysing different approaches to the planning process for the Campos basin. However, the methods developed may be applicable to other regions and countries as well.

The next chapter gives a further introduction to both the current and future situation at Petrobras, especially focusing on the logistic part of the value chain. In Chapter 3 the actual problem is described in more detail, narrowing the scope of the study down to only some parts of the logistics. Chapter 4 provides a comprehensive literature review, where subchapters focus on the different relevant problem types related to the problem described in Chapter 3. Following this, different models are developed and formulated mathematically in Chapter 5, while Chapter 6 proposes an alternative model formulation to the ones presented in Chapter 5. Chapter 7 explains how the models are implemented in the optimisation software, while the cases for the analyses are described and justified in Chapter 8. Test results are analysed and discussed in a comprehensive analysis in Chapter 9, before the final chapters present conclusions and potential future research.

Chapter 2

Background

This chapter gives further insight into the situation at Petrobras. The information obtained will be processed and used in the subsequent chapters, capturing Petrobras' situation and to develop a planning tool. Section 2.1 takes a deeper look into today's logistics system at Petrobras, including how supply orders are handled and the current platform supply vessels, routes and departures in use. In Section 2.2 different problems and bottlenecks are summarised, and possibilities in altering today's situation is discussed with the aim of overcoming obstacles in reaching future goals.

Petrobras operate along the Brazilian coastline, which is divided geographically into different basins, each consisting of several oil fields. Figure 2-1 shows the different basins southeast in Brazil with some of their major fields. A basin is operated from an operations unit onshore administrating all processes within the boundaries of that particular basin. Furthest north of the basins southeast lays the Espiritos Santos with headquarters located in the city Vitória. In the area surrounding Rio de Janeiro there are two basins: Campos basin and Rio basin. Due to their close proximity they will further be referred to as Campos. Santos basin lays in the south, and is the most promising area with regard to future exploration and production. The Campos and Santos basins hold the vast majority of Brazil's proved resources, and more than half of the country's production of crude oil stems from only six fields in the Campos Basin. As noted in the introduction, this thesis is restricted to the Campos basin. The Campos basin is operated from the logistics unit in Macaé, servicing the offshore installations from the Imbetiba port (TAI).

Petrobras will be the sole operator and own at least 30 % of the new large discoveries mentioned in the introduction (EIA, 2013). Their plan to double the production of hydrocarbons from the Brazilian shelf within 2020 will require improvements in all processes of the supply chain.

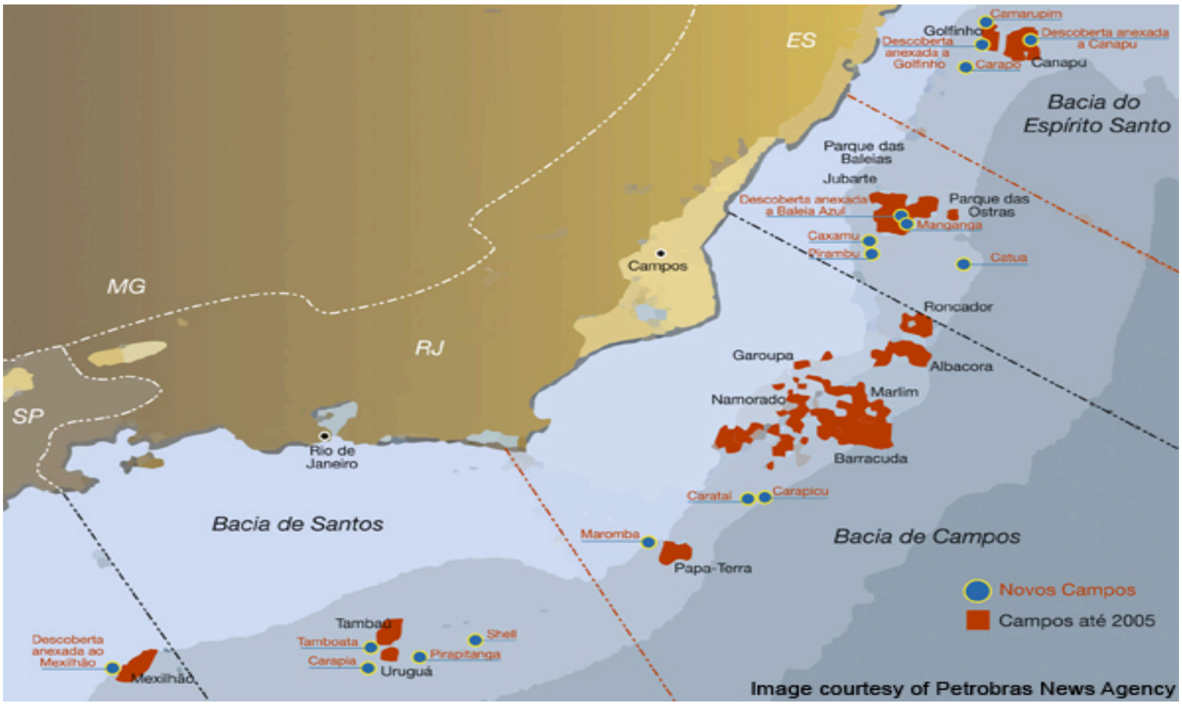

Figure 2-1: *Basins southeast of Brazil (Petrobras, 2013)*.

2.1 Logistics at Petrobras

The following subchapter gives an overview of the logistics operation unit (UO-LOG), which is stationed in the small city Macaé, located approximately 200 kilometres north-east of Rio de Janeiro. The logistics system can be divided into four levels, combining warehouse and packing as the first level, and where the remaining three are: ground transport, port operations and maritime transportation (Guedes, 2013). Figure 2-2 illustrates this division. The main task of the logistic unit is to manage resources between the mentioned levels, where they are responsible for both the onshore and offshore transportation of cargo.

Figure 2-2: *Logistics chain, Macaé (Guedes, 2013)*

Goods are transported from warehouses to the cargo terminal. There is one depot, which is the Imbetiba port in Macaé. The depot is responsible for receiving and allocating the cargo onto ships, where the vessels take over once the cargo is loaded. All supplies are shipped out from the depot to different offshore facilities located in the Campos Basin. Since capacity is restricted both on vessels and at the depot there is a need for efficient allocation and integrated operations for these processes. An overview of the logistics system is shown in Figure 2-3.

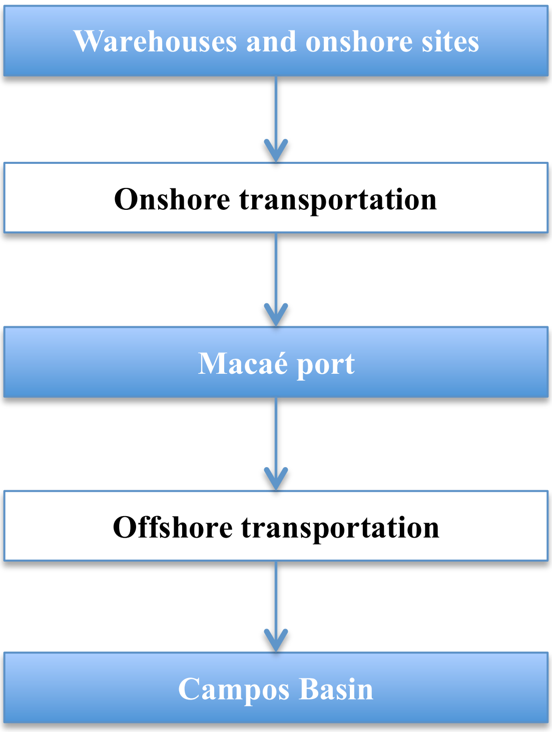

Figure 2-3: *Logistics system at Petrobras*

There are many offshore facilities in the basin with different characteristics depending on their function. The majority are production platforms, but there are also storage facilities and multi-use units. These offshore installations are in need of regular supplies of commodities from the mainland. As mentioned in the introduction, specialized supply vessels are used for this purpose. Due to restricted capacity on the offshore sites and the nature of supplies, some of the goods also have to be picked up and transported back to the depot. Most returned cargos are empty load carriers, waste, rented equipment and excess backup equipment. The sizes of orders are to some extent proportional to the size of the platforms requesting them and moreover depend on the operations on the platform in question. Drilling installations have more fluctuating and uncertain demand patterns for supplies than producing installations because of the complex nature of drilling

(Aas, 2009). Periods of construction work or adjustments may also require more supplies than when a platform is running in a normal mode producing from a developed field.

2.1.1 Order handling

The following gives a further insight into the chain of events from an order being requested to its delivery and the underlying issues at each level of the logistics system. The complete supply order process is illustrated in Figure 2-4. When a platform places a delivery request the order is received at the logistics central at the port in Macaé, where all orders are collected. Decisions are made on a regular basis regarding which orders to ship out on the next departures and the requests for those orders are sent along to the warehouses.

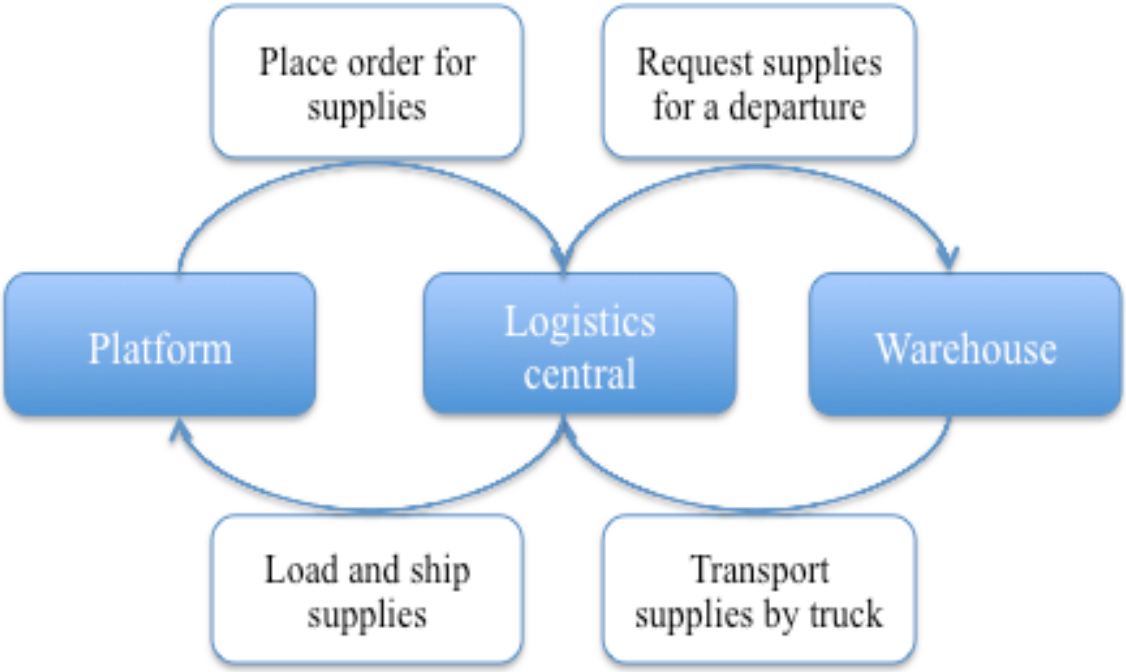

Figure 2-4: *Supply order process*

Warehouses and Packaging

All warehouses are located within close proximity in Macaé. When the request reaches the warehouses it is manually picked from shelves. Besides handling incoming supply requests for the offshore platforms, the warehouses are responsible for the control of inventory. The picked supply request is typed into SAP, a tool used to keep track of inventory in stock and to integrate logistics tasks (Friedberg, 2012a). As employees are manually updating stock levels the inventory process is vulnerable to human errors like mistyping and placing items at the wrong shelves. Another challenge at the warehouse level is over-utilization. Due to the increasing demand from offshore facilities combined with a lack of inventory space there is a need for building new warehouses in the area. There seems to be a complicated infrastructure surrounding the area, which limits the possibility of constructing new warehouses. Many orders seem to be delayed due to inventory control and stock-levels not being satisfied. When the ordered supply is picked and registered in SAP it is placed inside a cargo. The cargo is then loaded onto trucks, and the warehouse operation is relieved at this stage with the order proceeding to ground transport.

Ground transport

The responsibility for the cargo is now in the hands of cargo consolidation. Their main task is administrating the cargos at the warehouses, where they decide transportation mode, size, destination and priority of the cargo. External actors respond to demand from the cargo consolidation and conduct the ground transport of the cargo from warehouse to port. As cargo consolidation decide how cargos should be prioritized they are a part of deciding how the different platforms should be prioritized as well, making them relevant in PSV routing. One of the major difficulties they face is distinguishing between normal and emergency order requests. At the time being, 50 % of orders are characterised as emergencies without this necessarily being the case as the claimed fraction is supposed to be 10 % (Petrobras, 2014). There is also a time window for delivery at port and approximately only 75 % of cargo is delivered to the port in time. The remaining 25 % is further referred to as no-shows (Petrobras, 2013).

Port operations

When cargo with the requested supply order reaches the port, port operations take over. The port in Macaé is called Imbetiba, and it features three piers. The harbour is divided into several sections depending on it being shipment or backload cargo, and where chemicals and other special cargo are separated from the rest. Port operations are responsible for all tasks between cargo arrival from warehouse and loading/offloading on/off platform supply vessels. Trucks, cranes and trailers are in use for these everyday tasks. There is a time limit for when they can arrive in order for the supplies to be loaded on board the vessel, since this is a time consuming process as well. Orders arriving too late have to remain at the port or be transported away and wait to be rescheduled on a later departure. The port is running at maximum capacity, and it is consequently not possible to store large quantities of supplies there. Vessels can not lie at dock for a longer time than planned either, because of the limited harbour space. Figure 2-5 shows a picture of the Imbetiba port at Macaé.

Figure 2-5: *Imbetiba port at Macaé (Petrobras, 2013)*

Maritime Transport

When cargos are loaded onto supply vessels all that remains is shipping the supply orders to the requesting platforms. Maritime transportation handles this last part of the logistics level, and are responsible for monitoring the activities of vessels. The monitoring is done through a system tracking the movement of vessels, as each vessel is equipped with cameras and GPS.

2.1.2 Platform Supply Vessels

Petrobras have a large fleet of vessels at their disposal, where each platform supply vessel (PSV) is utilized to supply offshore platforms. Transported supplies can be divided into two main categories: deck cargo and bulk cargo, with bulk cargo being either dry or liquid. Depending on what type of bulk cargo they are loaded in separate storage compartments below deck. Containers of different dimensions carrying goods, pipes and other equipment of different sizes are stowed on deck. There are capacity restrictions for both types of goods, but historical data shows that the deck capacity is the binding capacity resource for the supply vessels (Halvorsen-Weare et al., 2012). Thus all demands from offshore installations are given in square meter deck capacity. Bulk supplies are usually not difficult to allocate compared to deck, and are disregarded throughout this study.

The different PSVs are classified by dead weight tons, with 1500, 3000 and 4500 being the most common in Petrobras. PSV 1500 and PSV 3000 are used to serve more fluctuating demand and express deliveries while PSV 3000 and PSV 4500 is mainly used in shipping commodity goods, which at the moment has standardized features at Petrobras. A picture of a PSV 4500 is shown in Figure 2-6.

Figure 2-6: *Petrobras PSV 4500 (Guido Perla & Associates, Inc., 2014)*

Chartering and operating supply ships are very expensive activities and external companies lease most of the PSVs at daily rates. In some cases, when supplies are urgent or special requests are made for other reasons, express deliveries are scheduled on short notice. This requires leasing another vessel, which is conducted on a 12-hours basis depending on the necessity. The cost of express vessels is approximately set to the double in daily rates compared to the scheduled vessels conducted by contracted ships. In addition, there exists no fixed or given routes for the express departures, and they may attend any offshore facility. Following this, most express are leased for a week at a time due to the uncertainty in voyage duration.

2.1.3 Routes and departures

Petrobras currently uses fixed route and departure schedules for the supply vessels. This was implemented to ensure predictability and trust between the supply chain participants, as the use of dynamically generated routes in the past resulted in various problems. For a departure, a vessel leaves the depot and visits a number of platforms before returning back to the depot. The journey may take several days depending on the distances travelled and loading missions along the route. Figure 2-7 is an illustration of a PSV route for the Norwegian oil company Statoil. The red squares represent oil fields. As one can see from the figure some installations are included in two routes and others in one, where all routes start and end at the same depot. In Petrobras' case the routes are constructed in a similar manner. Statoil is used as an example as an equivalent map could not be obtained for Petrobras, but the routes have the same characteristics.

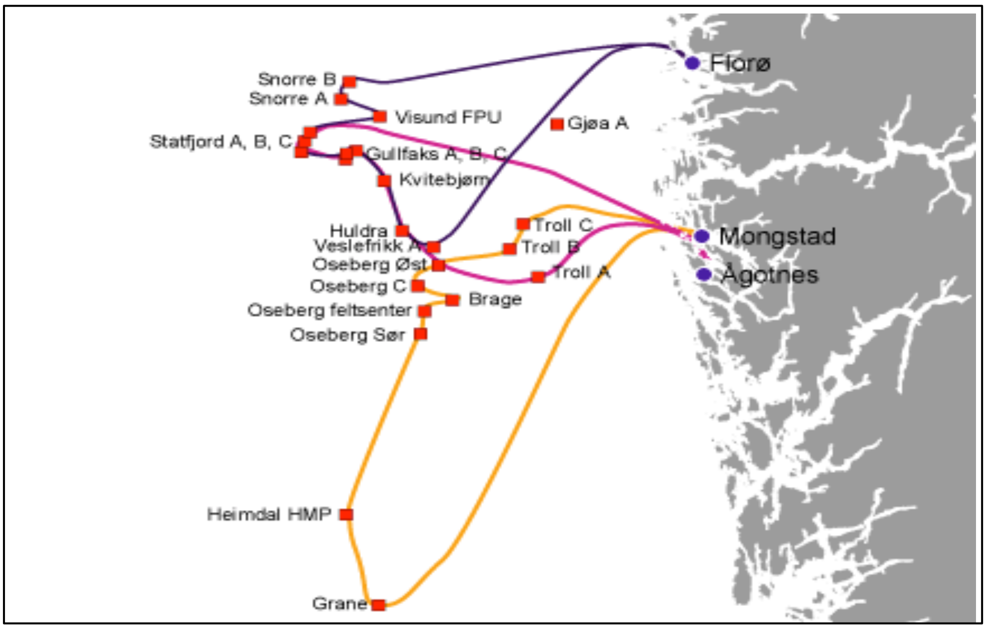

Figure 2-7: *Example of PSV routes*

The schedule for fixed routes and departures currently operated by Petrobras is presented in Table 2-1. A complete routing schedule obtained from Petrobras and a complete overview of the yielding names of offshore installation and routes with their corresponding numbers and labels can be obtained from Appendix A. Each PSV has a time limit of approximately three days to retrieve to the depot with the picked up backload after their given departure. During a week, 13 routes are travelled. Six of seven days consist of two fixed departures at 12:00 and 24:00, and only one departure is sheduled on every Monday. Different vessels take the different departures, where each vessel can be used for up to two voyages a week.

The schedule in Table 2-8 shows 52 offshore installations (platforms) being serviced at the moment, and a PSV visits a number between six and nine of these platforms in a given departure. 46 of 52 offshore installations are currently being visited two times during a week (once every three-four days), where the remaining six are only visited once. Altogether, 52 platforms are serviced through 13 departures in the duration of a week.

Day	Time	Departure	Platforms	Route								
Mon	24:00	**1**	6	[1	26	35	37	38	40]			
	12:00	**2**	7	[2	7	12	15	3	4	46]		
Tue	24:00	**3**	9	[18	19	20	27	32	33	44	39	5]
	12:00	**4**	7	[10	11	6	13	14	16	17]		
Wed	24:00	**5**	9	[21	22	25	31	30	36	41	23	24]
	12:00	**6**	8	[28	29	8	9	43	45	34	42]	
Thu	24:00	**7**	7	[2	7	12	15	46	3	4]		
	12:00	**8**	6	[1	26	35	37	38	40]			
Fri	24:00	**9**	7	[10	11	6	13	14	16	17]		
	12:00	**10**	9	[18	19	20	27	32	33	44	39	5]
Sat	24:00	**11**	8	[28	29	8	9	43	45	34	42]	
	12:00	**12**	7	[21	25	31	30	36	41	24]		
Sun	24:00	**13**	8	[22	47	48	49	23	50	51	52]	

Table 2-1: *PSV schedule at Petrobras*

2.2 Problems and bottlenecks

Offshore transportation is perhaps the most costly part of the supply chain, where costs like fuel, docking fees, operating costs and capital expenses must be taken into account. Hence, it exists large potential savings from focusing on good planning of vessel chartering. By summarising the consequences of bottlenecks from Section 2.1, especially focusing on the chain of events form orders being requested and up to their arrival at port, one of the largest concerns is that many orders do not make it to the port in time. This includes warehouses, packaging and ground transport. And when the orders do reach the port, the port is running at maximum capacity and it is consequently not possible to store large quantities of supplies there. In addition, vessels can not lie at dock for a longer time than planned because of the limited harbour space. This leads to underutilisation of ships, over constrained capacity at the port, excessive use of express vessels and higher costs for inventory and transportation.

Cost savings could arise from dynamic generation of routes and schedules, but problems related to human actions have overshadowed this potential in the past. Petrobras have previously experienced many difficulties due to the lack of trust between different parts of the logistics system. This was especially the case when short-term plans were concerned, as each part seemed to sidestep the guidelines given to make sure their own demands were met in a satisfactory manner. For instance, express deliveries were ordered quite often without any actual urgency of delivery. Fixed routes and schedules were implemented to create more predictable and to reduce some of the issue. But the problem still seems to exist.

Creating trust is a time consuming process, which will require improvements of all parts of the value chain. Even if fixed routes and schedules are implemented to reduce some of the problem, the issue is still present and in need of further exploration. In addition to no-shows, 50 % or orders are requested as emergencies where further express departures follow. A reason for the frequent use of the emergency label on orders is that platforms in need of demand places orders even knowing that it may take up to three-four days before their requests could potentially be planned met. As the previous section mentioned, the time lapse between services to a given platform is approximately three-four days.

The present study aims at addressing the problems as of today by simulating the situation through a model and applying alternative strategies and proposed solutions. The cost savings are potentially large and other factors affecting supply chain satisfaction should be considered. In the next chapter, the actual problem is described in more detail.

Chapter 3

Problem Description

Due to the heavy expansion plans at Petrobras there is a pressing need for higher efficiency, as the increasing activities offshore do not seem to reflect a corresponding increase in onshore capacity (Friedberg, 2012a). Petrobras' organizational objectives are to reduce investments costs, increase operational efficiency and reduce operational costs (Guedes, 2013). This study focuses on the two latter objectives.

At the time being, the depot at Macaé seems to be struggling in handling demand. PSVs are a costly resource in the offshore supply chain and it seems that the smallest improvements could potentially constitute huge savings (Halvorsen-Weare et al., 2012). The scope of this thesis is as earlier mentioned concerning the logistics unit (UO-LOG) at Imbetiba port (TAI), which is located in Macaé. The purpose is to examine the defined part of the logistics system with the intention to uncover potential cost saving areas that can be of significance for the future. The aim is to develop a practical tool for logistics planning and use this to analyse different approaches to the planning process. This chapter presents the problem addressed and the description is based on the information given in Chapter 2.

In creating a realistic analysis incorporating both the situation as of today and exploring new solutions, some general premises and assumptions need to be stated. The strategic decision of fleet mix and size is outside of the scope of this thesis work, as the fleet of PSVs is given and fixed. Also, the deck capacity on platforms are not considered, as it is assumed that there are enough space at all times in handling the delivery and pickup requested. Ultimately the goal is to serve all orders as quickly as possible at a low cost. It would be ideal if all orders could be served when they become known. One issue is that the total demand for a departure may exceed the capacity of the scheduled vessel, forcing some orders to be left behind. Another is the late arrival of a large share of orders, where previous statistics for Petrobras show that approximately 25 % of all orders being serviced do not show up on port in time for arrival. In addition, as order requests are made without considering the fixed departure and service of the corresponding platforms, orders have to wait up to 3-4 days before being processed. The objective of the logistics system is many-folded. Costs are essential and should be minimised, ship utilisation should be high, and platform orders should be served in a quick manner. Based on the conditions and findings in the system today, a model is developed to reflect the present situation, where different proposed solutions regarding routes, strategies and policies are tested to make it better.

The problem described is divided into three different levels concerning the routing policies applied. The first level imitates the present situation with the use of fixed routes and schedules, as currently operated at Petrobras. The purpose of the first level is to capture the situation and potential bottlenecks as of today, and to create a comparison basis for when further approaches and solutions are proposed. In the second and third levels the existing fixed routes and schedules are challenged, where flexibility and dynamic generation are added respectively. Table 3-1 summarises the different problem levels considering the route policy applied, where suitable names are chosen at each level.

Level	**Name**	**Description**
1	The Supply Order Problem (SOP)	Imitating the present situation at Petrobras with the use of fixed routes and schedules
2	The Supply Order Problem with Flexible Routes (SOP-FR)	Allowing the exclusion of platforms in the predetermined routes
3	The Supply Order Problem with Dynamic Routes (SOP-DR)	Generating routes dynamically based on orders requested

Table 3-1: *Problem levels concerning route operations*

Following this, a more in-depth explanation of each problem level is given below before the objective is presented.

The Supply Order Problem (SOP)

The study in this thesis is initiated by problem level 1, which imitates the actual situation at Petrobras. As earlier mentioned, Petrobras have incorporated routines regarding the service of supply orders that involve fixed PSV routes and schedules, and a given procedure that the relevant supply chain participants follow. It is assumed that all platforms given in a fixed route has to be visited during the voyage. As the distance travelled is already set, no more attention is given to the actual voyages and the corresponding costs. With fixed routes in place it is needless to say that a routing problem is unnecessary, and problem level 1 will be further referred to as a simple supply order problem (SOP). In addition, priority would not be given to time constraints or vessel performance, but rather to a true representation of the order cycle at this instance. The offshore installations considered are mostly production platforms, but some drilling platforms are also included, and the amount of orders requested changes accordingly.

The focus in this level is using details around the given routes, capacity on vessels, typical orders and platform characteristics. The objective is to minimize costs when orders are served considering which orders to include and which to delay at each departure. Hence, the only cost included at this instance is the inconvenience of delay for cargo that is delivered overdue. This inconvenience cost should be based on different elements like the priority of the cargo, order size and time of lateness. In addition, express departure costs are taken into consideration for emergency orders that are not serviced by regular departures due to no-shows, capacity restrictions and so on. The inconvenience of delay for emergency orders are set high relative to other inconvenience costs to ensure that emergencies are primarily allocated on regular departures.

The Supply Order Problem with Flexible Routes (SOP-FR)

At the second problem level, the existing routines as presented in the SOP are addressed with the use of appropriate means. A new method is needed to improve the integrated logistics system, and the main objective here is to explore such a method and make use of it to see its implications for existing challenges within the frame of Petrobras' current operations.

Optimisation methods are not commonly used in the oil and gas industry for planning of supply distribution. Aas (2009) explains this by the low competence level of logistics planners in oil companies and the lack of research in the area. Previous literature has paid much attention to general routing problems, but not for supply vessels in particular or for logistics problems with predetermined routes. A further progression in the offshore transportation area is to take the fixed routes and schedules currently in use a step further by proposing some degree of flexibility. The current fixed departures with their corresponding routes and platforms visited is still in use, but the option to exclude platforms from a given departure is proposed as an alternative. The problem at level 2 will further be referred to as the supply order problem with flexible routes (SOP-FR).

Planning for a departure in the SOP-FR means deciding which orders that should be serviced or not balanced against which platforms in a given route that should be visited. Savings could potentially be obtained in situations where additional demand is served to one platform at the cost of excluding others. With such a route policy applied, one would not expect any significant changes in order delay, as no additional platforms than the ones already existing in the predetermined route are visited. On the contrary, additional delays could potentially follow if more weight is placed on reducing travel costs. And with more delays, additional express departures could potentially follow. However, this depends on the attention given to actual order service compared to voyage duration. Nevertheless, costs could be saved, and it is interesting to see whether this is possibility without the expense of worsening the situation service-wise.

The Supply Order Problem with Dynamic Routes (SOP-DR)

Potential cost savings could arise from dynamic generation of routes. As mentioned in Chapter 2, problems related to human actions and cooperation between different parts of the supply chain has weighted against such strategies in the past. Even so, investigating this as an options is still of interest, as the use of fixed routes has proven little effective when supply chain trust is considered. Problem level 3 aims at doing exactly this by using completely dynamic routes as an alternative to the predetermined departures currently yielding, which will further be referred to as the supply order problem with dynamic routes (SOP-DR).

As mentioned, frequent delays and corresponding express departures are followed by the fixed route policy currently applied, as 25 % of the orders requested do not show up at port in time for departure. Orders are requested without regards to the routes applied, where delays of 2-3 departures follow from this alone. Dynamic generation or routes could potentially reduce some of the problem, as the voyage is based on the demand requested. Hence, which platforms to serve, in what sequence and service operations are all decisions that have to be made when optimising the route for a given departure.

Objective

Put together considering all problem levels presented, the objective of this thesis is to analyse how alternative planning-strategies based on developed models and methods potentially can contribute to minimize the costs of servicing orders to platforms. Depending on the level and corresponding route policy, these costs include inconvenience costs due to order delays, travel costs and express costs. When 25 % of orders are no-shows the use of fixed routes may result in visitation of platforms that a given departure is not able to serve, which adds unnecessary travels cost. This problem is confronted in both levels 2 and 3, where flexibility and dynamic generation are proposed as possible solutions. In addition, frequent express leasing follows large delays of orders and emergency requests. As the express vessels for such operations are not limited by a fixed schedule, they are easily available and used active. This is an extremely costly operation. As earlier mentioned, reductions here may constitute in potentially large cost savings.

As an extension of the study made in Gausel and Hagen (2013), testing the SOP as of today at Petrobras with the use of different policies and strategies should be explored in addition to the routing part. One such policy is the use of overbooking when planning for a departure, which means intentionally selling more cargo space than the available capacity to compensate for no-shows, cancellations and other variations. This showed a large potential in Gausel and Hagen, and is further explored in the following study. In addition, the impact of reducing no-shows and false prioritisation of orders for the SOP is presented, where the objective is to examine the cost saving potential for Petrobras if they managed to improve their onshore logistics considering these flaws. Altogether, the ultimate goal is to create a comprehensive analysis comparing the different problem levels presented above, both internally and with each other.

Chapter 4

Literature

In this chapter an overview of the operations research literature concerning the problem addressed in Chapter 3 is provided, where related findings and topics explored in various academic papers will be summarised. The problem at hand is a combination of two parts: finding the optimal allocation of orders in a supply order problem (SOP), and optimizing the routes and schedules conducted. The first part can from an optimization point of view be seen as a simple pickup and delivery problem. According to Savelsbergh (1995), "*vehicles have to transport loads from origins to destinations without transhipment at intermediate location"* in this problem class. The objective is to minimize the inconvenience costs that may occur if demand is delayed. Much of the literature considering this part points out that allocation problems are often influenced by transportation costs. To the author's knowledge the study of problems with fixed routes as for the simple SOP are very limited. Most problems involve determining the route, as this is considered the main challenge.

In problem levels 2 and 3 on the other hand, the second part becomes evident, as the distances travelled are considered in addition to solving a SOP. Problem level 2 applies flexibility in the predetermined routes, while routes are generated dynamically in problem level 3. Both problem levels are however solved while fulfilling pre-requested delivery and pickup demand to a set of offshore facilities. As the latter paragraphs point out, it is difficult to view the two problem parts mentioned separately. Literature based on the SOPs is scarce, and the routing and scheduling are affected by the requested demand. Hence, it seems valuable to look at literature combining the two.

In the following, articles addressing the optimization topics mentioned above are presented. Section 4.1 contains literature concerning both order allocation and routing, as much of the existing studies combines the two. The shipping segment is emphasised in Section 4.2, with routing for ships in particular. Literature about simulation in combination with optimisation has also been reviewed. Special attention is given to the rolling horizon principle, as the present study incorporates several departures. Useful articles concerning this topic are presented in Section 4.3. Some models and solution methods are discussed for the various topics, aiming to build a good foundation for understanding the problem at hand and for developing models in the next chapter.

4.1 Vehicle routing and order allocation

In general, vehicle routing problems are problems seeking to find optimal routes from one or several depots to a number of destinations, such as cities or customers. Different constraints may apply for variations of the problem. The models are central in planning of physical distribution and logistics (Laporte, 1992). The vehicle routing problem is an expansion of simpler models like the shortest path problem and the travelling salesman problem.

In addition to the arguments made in the introduction, there are two underlying and related reasons for including this literature in the current study. First, it is believed that it is important to have a clear understanding of the problem structure and the differences between well-known theories and methods. For instance, the inclusion of capacity constraints in addition to pickups and deliveries may have similar impacts already in the simple SOP as for routing problems. Second, and most important, the literature review in this section especially supports the further progress of the SOP incorporating alternative routing operations. Comments will be made along the way on the findings to explain its usefulness based on its similarities and differences to the problem addressed.

The traveling salesman problem (TSP) is chosen as a starting point in this literature review because of its resemblance to the problem described in Chapter 3. The TSP is in its simplest form a vehicle going from a depot and delivering goods to a given set of customers before returning to the depot, where all customers have to be visited once and the objective is to minimise the travelling costs or the travelling distances. The TSP is a classical problem in discrete or combinatorial optimisation and belongs to the NP-hard classes, that may require an infeasible processing time if solved by an exhaustive search method (Geng et al., 2011). Heuristics are therefore commonly used to obtain near optimal results in a shorter time. Figure 4-1 shows an illustration of a possible solution to a TSP, with costs for each arc between customers.

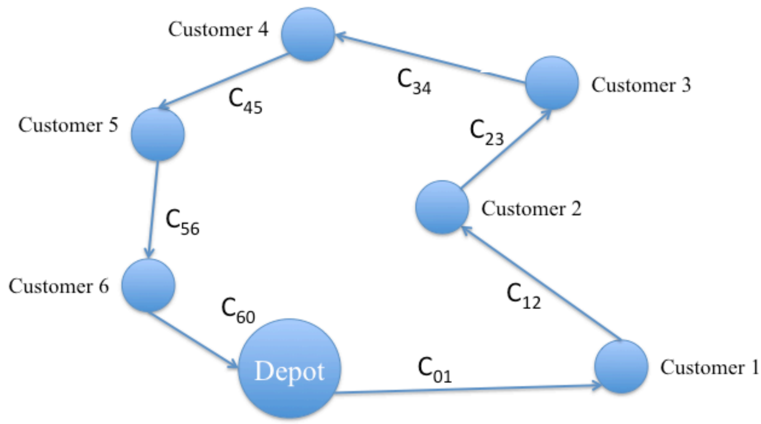

Figure 4-1: *The travelling salesman problem*

Compared to the TSP any PSV sailing a given departure plays the same role as the single vehicle, the port in Macaé represents a single depot where all routes start and end, and the different offshore facilities are the customers. When only a simple SOP is considered the biggest difference related to the TSP is the objective of the models. The TSP aims at designing the least costly route while the SOP at level 1 aims at serving orders with minimised delays. In addition, the constraints for one departure are related to the load and vessel capacity. The TSP is by definition not capacity constrained, but such restrictions are found in many modifications of it.

Mosheiov (1992) studies a capacity constrained problem where he first assumes that the sum of demand quantities is equal to the given capacity. If the demand is higher there is no feasible solution to the problem when all demands have to be met on the given journey. The problem becomes easier and more similar to the normal TSP when total demand is less than the capacity, as this will not be a binding restriction. Louveaux and Salazar-Gonzalez (2008) generalise Mosheiov's approach by instead considering stochastic demands in a TSP. In this model the demand is a random variable leading to different scenarios with known probabilities. Vehicles are assumed to have a fixed capacity and leave the depot with an initial load. A route is feasible if all customer demands are satisfied given this capacity, and a penalty is proposed for routes where the vehicle is not able to meet demand.

The papers presented in the previous paragraph are relevant for the problem at hand, especially when the simple SOP is considered. The SOP incorporates two items of stochastic nature: the order generation, as the number and demand quantities of orders become known periodically, and the presence of no-shows. On some days order demands for the given departure may be higher than average, where certain orders can not be taken in the current period due to vessel capacity. This is in a way similar to the stochastic demands considered by Louveaux and Salazar-Gonzalez, who propose a penalty cost for demands exceeding the vehicle capacity. No-shows are the orders that arrive at port too late to be taken on the planned departure. Information about these orders becomes available only after the time limit for re-planning is reached. Stochastic demands as defined by Louveaux and Salazar-Gonzales are present in this case in the shape of no-shows. It is equivalent to uncertain demand, since the no-show orders are unknown. There is however an expected share of no-shows with fluctuating patterns. Similar to the stochastic arrival of order requests, a penalty cost may be imposed on the orders that arrive late and must wait for a later departure. The objective function is formulated to minimise penalty costs for delay of orders, either simply due to a constrained vessel capacity or no-shows.

The present study is somewhat complicated by the combination of pickups and deliveries that may be requested by a platform in the same departure. These elements are however all present in a capacitated single vehicle pickup and delivery problem. Parragh et al. (2008) did a comprehensive study considering this problem class, where they define four subtypes based on sequencing rules: deliveries must be made before pickups; any sequence is permitted; and customers demanding both pickup and delivery can be visited once or twice for simultaneous or mixed pickups and deliveries, respectively. Pickup and delivery is in general easiest when deliveries are made before pickups, but this is not always possible (Mosheiov, 1992).

Min (1989) was the first to tackle simultaneous VRPPD, where the customers where clustered into groups before TSPs were solved for each group. All infeasible arcs are penalised and the TSPs solved again. Halse (1992) did a similar study using a cluster-first routing-second approach, where at the first stage an assignment for customers vehicles is performed, before a routing procedure based on 3-opt is used. When dynamic generation of routes is proposed as an alternative solution to the fixed routes, each departure consists of requested demands where travelling distances between platforms and vessel capacity restrict all demands from being served. A cluster-based approach may be useful when deciding on the platform set for the given departure.

Considering the long distances and great costs in fixed routes and schedules currently operated, a VRP with simultaneous delivery and pickup is appropriate when the capacity allows it. Otherwise, two such orders from the same platform would have to be served on two different journeys, as the current operations at Petrobras only allow one visit to each platform. In cases where platforms request both pickup and delivery with pickup being the larger, the vessel capacity may restrict the pickup service from proceeding. Allowing two visits to a yielding platform may cope with this, as excess capacity is freed if other deliveries are conducted on platforms in between visits. Consequently, investigating this as an option when routes are made dynamically is presented.

The mixed SVPDP has gone under names like the TSP with pickups and deliveries by Mosheiov (1994), the TSP with delivery and backhauls by Anily and Mosheiov (1994), and the mixed TSP by Nagy and Salhi (2005). The relevant paper by Nagy and Salhi (2004) allows for two visits per platform during a route with the yielding assumption "pickups after deliveries". They propose a method that treats pickups and deliveries in an integrated manner where they find a solution to the corresponding VRP problem and modifies this to make it feasible for the VRPPD. Modifications are achieved mainly by the use of heuristics from VRP methodology. If for example they have a situation with too many customers with large pickups and small deliveries at the beginning of the route, the route will be made infeasible. Reversing such a route will make it feasible, as it will serve the large deliveries first and the large pickups later on.

When allowing two visits to a platform, serving pickups after deliveries seems like a safe assumption to make. There exists no reason to save a delivery for a second visit, as additional deliveries only increase the load on board the vessel. In addition, it would never be optimal to pick up an order at the first visit when planning a second visit to the same platform, as the additional pickup load may restrict other pickup operations to be performed for platforms in between.

In the present study the demand for each order is measured in the same unit, that is deck area. But the orders are unique and must be served for the particular customers requesting them. Hence, orders are classified as multi-commodity goods, where each order is one specific commodity. Psaraftis (2011) presents a dynamic programming algorithm for solving a multi-commodity capacitated pickup and delivery problem, incorporating both a single and two-vehicle cases (MCCPDP). The objective function includes both vehicle trip costs and cargo delay costs, which is similar to the objective in this study considering the routing aspect as well as the SOP.

In addition, all supplies ordered are transported from the depot to the respective platforms, and pickup orders are transported from platforms and back to the depot in the same route. This is further classified as a "one-to-many-to-one problem", which is studied by Gribkovskaia and Laporte (2008) in their one-to-many-to-one single vehicle pickup and delivery problem (1-M-1 SVPDP). "One-to-many-to-one" is opposed to transportation problems with transhipments, where goods can be picked up from one customer and delivered to another. An illustration is shown in Figure 4-2, where all customers have deliveries marked by letters A, B, C and D, and customers 2 and 4 have pickups as well marked E and F that are carried back to the depot. A vehicle starts and ends up at the depot, and there are several possible variants on the sequence of pickups and deliveries (Parragh et al., 2008).

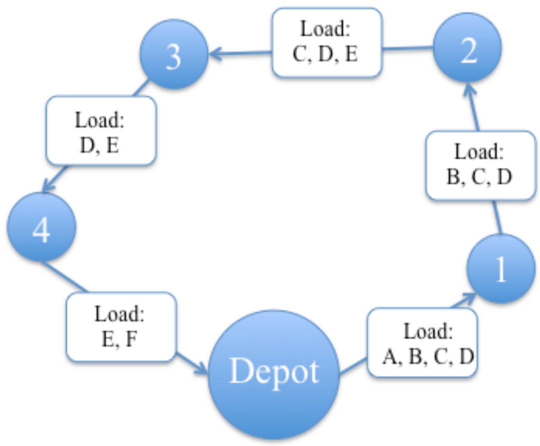

Figure 4-2: *One-to-many-to-one pickup and delivery*

Gribkovskaia and Laporte (2008) propose many extensions of the 1-M-1 SVPDP featuring similar aspects to the problem at hand. An example of such a similarity is the use of combined demand, where a given customer may request both pickups and deliveries during a departure. One extension they proposed where the use of periodic SVPDPs, where pickup and delivery requirements are spread over a period of several days. The problem then becomes to simultaneously determine a subset of customers and the order of visits for each day. Alshamrani et al. (2007) present a similar study, imposing a time limit between pickup and delivery operations in order to avoid product deterioration. As the problem description in Chapter 3 states, different priorities are coupled to orders. The use of similar methods to the ones described above when considering order priority should be explored in the optimization.

Another relevant extension provided by Gribkovskaia et al. (2007) is the use of SVPDPs with selective pickups, where pickups are optional but generate a profit when performed. They study a case by Privé et al. (2006), which considers the delivery of beverages to supermarkets and convenience stores, and the collection of empty recyclable containers. Ting and Liao (2012) present a similar study: the selective pickup and delivery problem (SPDP), where they relax the requirement that all pickup nodes must be visited. This is found to have a cost saving potential, and could be applied to other problems within both onshore and offshore transportation. The relaxation gives higher priority to the delivery demand compared to the need for pickup during a given route, which is also realistic for the problem described in Chapter 3. It is much more important to deliver new supplies than returning backloads, as delays in supply may constitute in production disruption. Pickups are mostly empty load carriers, waste, rented equipment and excess backup equipment, which does not affect platform efficiency.

All articles presented in this section examine problems with several similarities to the one considered in this thesis. In general, all articles were concerned with transportation processes where demands are to be picked up and delivered at various sites. Especially, as the latter paragraphs show, the paper by Gibkovskaia and Laporte (2008) consists of many parallels to the problem where routes are generated dynamically. Hence, using the 1-M-1 SVPDP model as a basis could potentially be of value. However, no articles consider problems where routes are already predetermined and given, or with the use of predetermined but flexible routes. Even if departures are given the option to exclude platforms from the predetermined route in the SOP-FR, platforms are coupled to sequence numbers, setting large restrictions on the routing part. To the author´s knowledge no such methods have previously been explored to the same degree as presented in Chapter 3.

There are many other possible extensions to the vehicle routing and scheduling problem. The inclusion of time windows for the possible times arriving and leaving nodes in the route can be relevant to many problems. This is omitted here because of the nature of the supply order problem where this is not of importance due to the predetermined departure schedule and the use of different vessels on different departures.

4.2 Offshore supply routing and scheduling

Ship routing and scheduling is less explored than vehicle routing problems, but many aspects are similar for the two. Ronen (1982) explains the lack of ship research by the fact that ship routing is less structured with more variety in problems and operating environments, and more uncertainty present due to for example weather or mechanical problems. The problem for Petrobras in this thesis involves the planning of supply vessels. The costs in shipping are high, meaning these factors can have a large impact and good planning is crucial. The industry has traditionally been conservative compared to onshore transportation.

Following this, the present section will present literature about offshore transportation and the ship segment, aiming to relate the theory closer to the problems described in Chapter 3. Reasons for this review are similar to ones in the previous section: to get an understanding of the problem in general and to explore how the currently fixed routes and schedules can be altered to the better, emphasising on the shipping segment.

Shipping in general refers to moving cargoes by ships. Christiansen et al. (2007) provide an exhaustive overview of operations research in maritime transportation with models and solution methods. They distinguish between liner, tramp and industrial shipping, and look at the traditional planning levels. Market and trade selection, network and transportation system design and fleet size and mix decisions are among strategic problems. Tactical problems include ship routing and scheduling, fleet deployment and container stowage planning. Routing is the assignment of choosing a sequence of ports to a vessel, while scheduling is assigning the times to these and other events on the route. The different vessels are assigned to routes, referred to as deployment. Lastly, operational planning concerns problems like sailing speed selection and ship loading. There is a significant overlap between the three planning stages. Operational planning is the most short-term stage, and can be essential when there is uncertainty and unpredictable event patterns. Some operational planning is targeted in tall three problem levels, while some tactical planning is included as well in the later levels where new routing policies are proposed. Strategic problems are outside the scope of this thesis. The following paragraphs review papers concerning the ship routing and scheduling problem taking into account both operational and tactical planning, stressing the previously mentioned characteristics from Section 4.1.

In the case of supply vessel planning, Halvorsen-Weare et al. (2012) did a study for Statoil where the optimal fleet composition of PSVs and corresponding weekly voyages and schedules are determined. They make use of a voyage-based solution method. In the first phase all voyages are generated by defining subsets of offshore installations that may be visited by a given vessel, and for each subset a TSP with multiple time windows is solved by full enumeration. The voyage with shortest duration is chosen. The second phase involves solving the model to choose cost-effective supply vessels and the best routes to fulfil the constraints. In the problem at hand, the first phase is already solved and left out since the routes and schedules are fixed and given. For problem level 3, where routes are generated dynamically it may be natural to include the routing of PSVs similar to what Halvorsen-Weare did for Statoil. Such a planning process has similarities to the vehicle routing problem, but can be more complex.

Gribkovskaia et al. (2008) introduce a pickup and delivery problem for servicing offshore oil and gas platforms in the Norwegian Sea. The problem is called the single vehicle pickup and delivery problem with capacitated customers (SVPDPCC), only there is a vessel instead of a truck and platforms serve as the customers. The planning is done for one vessel at a time. The SVPDPCC consists of designing a least cost vehicle route starting and ending at the depot, making all pickups and deliveries such that the vehicle capacity is never exceeded. They use vertexes in their model formulation, assuming that the available capacity at a vertex is always sufficient to perform delivery or simultaneous delivery and pickup, and that a fully laden vehicle never arrives at a vertex having zero capacity and equal pickup and delivery demand. Several construction heuristics and a tabu search algorithm are described as solution approaches. In addition, the problem presented in Gibkovskaia et al. (2008) is restricted by platform available capacities, where capacities vary from one platform to another and some part of platform is free space while the rest is occupied by containers. Aas et al. (2007) presents a similar study, where they formulate a mixed integer LP model with restrictions on vessel capacity as well as the capacity on the offshore installations.

Using capacitated platforms is not an issue in the problem evaluated, as it is assumed that there is always sufficient capacity on the platform and that a vessel easily can perform both on- and off-loading. When excluding the capacitated customer part (CC) in Gribkovskaia et al. (2008) the problem becomes similar to the one presented by the same author in 2007. This shows that the model is applicable for the shipping segment as well, which further argues its usefulness in the present study.

4.3 Optimisation with simulation

Simulation is used when it is impossible to directly or immediately observe the consequences of a proposed action or plan. The present problem is to plan when to deliver and pick up orders generated based on demand from different platforms. Orders not served in one departure should be processed in the next period, treated dynamically. When proposing different solutions to the present situation, the result may not be immediate when regarding a single departure alone. A simulation method could be applicable in these cases, where one departure is simulated at a time and record the results from all the past simulations.

This section explore the possibility of using simulation as a tool combined with simple optimisation models to overcome potential shortcomings of both running times and keeping the quality of the solution. Simulation is a widely used operations research technique due to its ability to handle stochastic elements, and there exists two types of simulation systems: discrete and continuous. They differ in how the variables change. Discrete systems are appropriate when state variables only change at certain points in time, such as when a vessel arrives at the depot and new orders become known (Aneichyk, 2009). Discrete event simulation has become important for managing operations research and computer science together. The need for improved handling of problems with a stochastic nature has not yet been met by a corresponding research in simulation optimisation, which can potentially cover these needs better than other methods (Fu, 2002).

Simulation enables testing decisions prior to actually making them, and permits the inclusion of uncertainty and variability into the forecasts of process performance (April et al., 2006). The method is needed because real world problems can become very complex. Richetta and Larson (1997) did some of the first work on using simulation with optimisation, developing a model for marine transportation of refuse. Discrete event simulation was used to model refuse generation, operations at the nodes in the transportation system and ship tracking. They found that the model performance was statistically stable and close to real life with simulation statistics for one year and one week transition as start-up.

Fagerholt et al. (2009) present a conceptual model for combining simulation and optimisation in maritime transportation. Figure 4-3 illustrates two ways of such a combination. The integrated approach is suggested to overcome the shortcoming of optimisation concerning stochastic elements, and also allows optimising routes and schedules, which simulation alone does not. Monte Carlo simulation is used to generate scenarios and evaluate solutions. The illustration to the right in Figure 4-3 illustrates such a stochastic programming process, which makes use of simulations as add-ons used to generate scenarios. These scenarios are further used for the mathematical programming formulation. Here, the simulation model gets input from strategic decisions based on optimisation and scenarios, and the analysis is performed iteratively. The method is found to be flexible and deals well with uncertainty, but the disadvantage is that it can be data demanding and time consuming.

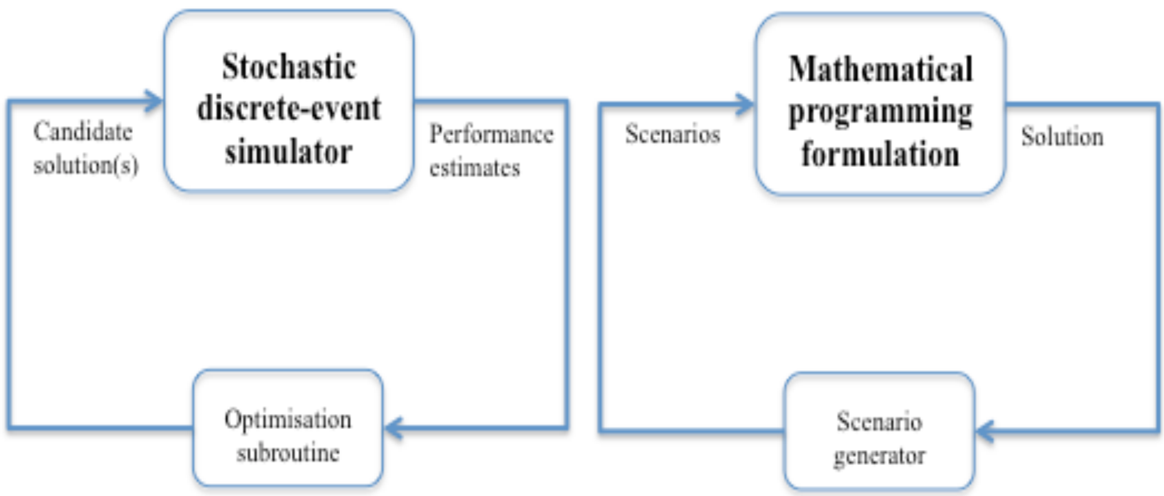

Figure 4-3: *Optimisation for simulation vs. simulation for optimisation (Fu, 2002)*

The approach explained by Fagerholt et al. with scenario generation may be useful in the implementation of the model for the supply order problem. With simulation an optimisation model can be solved in each departure when new information becomes available. The information about new order requests can be generated dynamically to imitate the actual situation for Petrobras where platforms require supplies at different times. In addition when the fixed routes are challenged, new routes are generated at each departure. Outputs from the optimisation and the simulation interact as bases for the decision-making, and are taken into account by a long-term objective function. For fixed routes and schedules, data and time consumption will probably not constitute important modelling challenges. When routes are altered however, the problem becomes more complex.

In a paper developed by Sethi and Sorger (1991) a theoretical framework for the practice of rolling horizon is explained, which is a way of making decisions in a dynamic stochastic environment. Here, the term "horizon" refers to the number of periods in the future for which the forecast is made, and it is this horizon that gets "rolled over" each period. The concept is demonstrated in Figure 4-4. This practice involves making the most immediate decisions based on a forecast of relevant information for a certain number of periods in the future. At the beginning of the second period, the second period decisions become the most immediate, and hence the horizon rolls. Forecasts for additional departures in the future may be required in order to make decisions, and existing forecasts may also be revised or updated. For the SOP, both with and without alterations in the routing aspect, the most immediate decisions have to be based on the information given prior to a departure. The relevant information includes the orders available for service and the corresponding platforms that should be visited. Each new departure represents a new decision stage, where decisions are made based on the available information including past decisions.

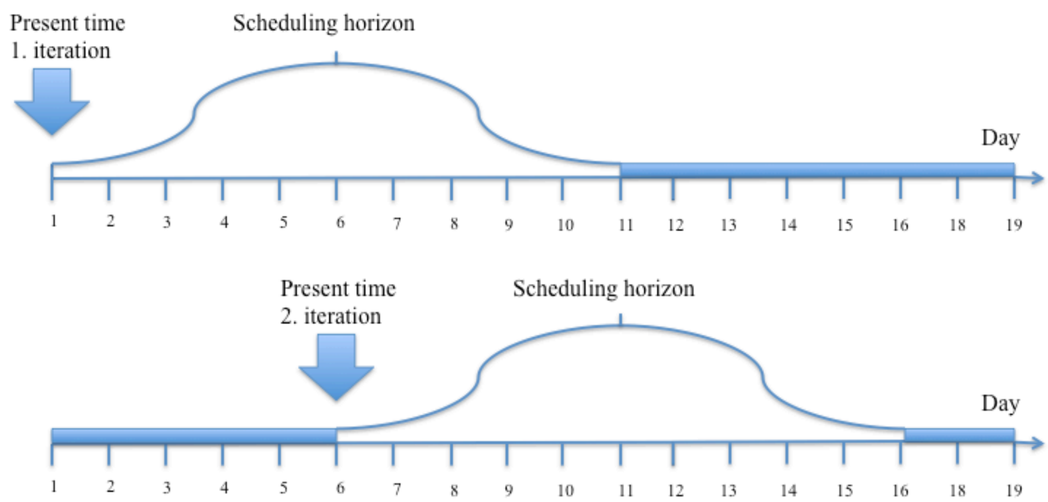

Figure 4-4: *Rolling horizon (Sethi and Sorger, 1991)*

Yang et al. (2002) address a real-time truckload pickup and delivery problem, where a truck is requested to handle only one request at a time. A fleet of truck aims to service point-to-point transport requests arriving dynamically and the authors propose a rolling horizon approach based on a linear program solved whenever a new request arrives. Chen and Xu (2006) design a dynamic generation algorithm for the same problem, where the concept of decision periods over the planning horizon is suggested. The decision periods represent the times when the optimisation process is run, by dynamically generating columns from the previous periods. These approaches are of relevance to the problem at Petrobras, as orders from platforms are received at different points in time and an optimisation program is solved periodically.

Chapter 5

Model Formulations

This chapter presents the mathematical formulations for the supply order problems (SOPs) with the use of different levels concerning how routes are operated as presented in Chapter 3. The models formulated are continuations of the SOP made in Gausel and Hagen (2013), which is taken a step further by exploring different alternatives to the fixed and yielding routes currently operated by Petrobras.

Altogether, four different models are formulated, as seen in Table 5-1. Each of problem levels 1 and 2 consist of a single model level each, namely models SOP and SOP-FR, respectively. Problem level 3 on the other hand, incorporates two models depending on platforms being allowed a second visit in the duration of a single voyage. With two models in use, level 3 is further divided into sublevels 3.1 and 3.2. As presented in Table 5-1, the corresponding model names SOP-DR-1 and SOP-DR-2 are given in relation to the number of visits allowed for each platform in a route.

Level	Name	Description	Route	Platforms
1	SOP	Imitating the present situation	Given, fixed	Given subset, all are visited
2	SOP-FR	Allowing the exclusion of platforms	Given, flexible	Given subset, some are visited
3.1	SOP-DR-1	Optimizing routes given the orders requested	Dynamic	No subset, all can be visited once
3.2	SOP-DR-2	Optimizing routes given the orders requested	Dynamic	No subset, all can be visited twice

Table 5-1: *Model levels concerning route operations*

This chapter is initiated by laying out some key assumptions used in the model formulations. Following this the different model levels are presented, viewing a single departure in isolation from the rest. At each level additional assumptions are stated before the mathematical models are presented. In the end, the SOP with the rolling horizon principle in use is formulated, which incorporates several departures. The rolling horizon principle illustrates how the different departures are coupled in the long run.

5.1 Main assumptions

All models are formulated for one departure in isolation from the rest of the planning horizon. The problem is to optimally decide which orders to serve, using both fixed, adjusted and optimized routes depending on the level. For a single journey, one vessel leaves the depot and visits a number of platforms where orders are served, before returning to the depot. Only orders for the platforms visited in the current departure can be served. Due to different constraints, not all standing orders for a given departure can be served immediately after they are requested. To find the best way of allocating orders in a departure, a cost is introduced to represent the inconvenience of delay. This cost may depend on the importance and the size of the order, whether it is a pickup or delivery request, and the length of delay. Costs concerning the distances travelled are included as well when model levels 2 and 3 are concerned. The models are formulated as minimisation problems, where the objective function is to minimise the costs incurred for one single departure.

5.1.1 Facilities

Facilities may be either offshore (platforms) or onshore (the depot). Hence, the term ‘facility’ covers both platforms and the depot in this setting. The set of all facilities is given by a list of identification numbers, where the depot is labelled as 0 while platforms are labelled as non-zero numbers starting from 1. For the one-departure problem, only a subset of the platforms from the list is visited. Deliveries and pickups are made according to order demand for the platforms, and hence a platform is coupled to each order and the corresponding demand quantity. As mentioned in chapter 3, the offshore platforms considered in this thesis are mostly production platform, but some drilling platforms are also included and the amount of orders requested changes accordingly. It is assumed that the platforms visited have the sufficient capacity to perform delivery, pickup or simultaneous services at all time, and that such operations are easily done. Hence, capacitated platforms are not an issue in this thesis.

5.1.2 Vessels

One vessel operates per departure and the vessel capacity is assumed fixed. The deck space capacity is an important parameter, as it restricts the amount of load on board the vessel at all time, which further restricts the amount of orders being served in a given departure. The shape of orders and deck are disregarded, assuming that an order can be carried as long as the total area on board the vessel is not exceeded.

5.1.3 Orders

The set of orders for the one-departure problem is a list of order numbers, where each order is linked to a specific platform. It is assumed that a platform places at most one pickup and one delivery request per period. However, at any point in time the order list may include orders placed in relation to previous departures. A platform can be visited without serving all its standing orders, so the orders are kept separate from each other. A demand quantity is given for each order in square meters according to the deck area needed to transport the supplies. In the long term, deliveries to a platform are greater than pickups. The difference in both size and number combined results in pickups being one third compared to deliveries.

5.2 Level 1: The Supply Order Problem

The supply order problem (SOP), where fixed and given routes is implemented serves as a starting point in explaining how orders are allocated. Some additional assumptions must be stated to create the mathematical SOP model. These assumptions are presented in the following before the various symbols used are formulated and the objective function and main constraints are described.

5.2.1 Additional SOP assumptions

As previously mentioned, the mathematical model is formulated for one departure. A departure is coupled to a single period in this setting, as each departure is already scheduled time wise and determined concerning the platforms served. Hence, the formulation is made for a single period seen in isolation form the rest of the planning horizon. And as the route for each period is fixed and predetermined, the SOP becomes to optimally decide which orders to serve. The vessel departs from the port and follows a predetermined route, visiting a number of platforms in a fixed and given sequence.

Facilities and routes

In the one-period problem there is only one route travelled, which is the relevant input given as a list of facilities visited. The list of facilities visited includes a subset of platforms and the depot. Only the subset of platforms for the single period is considered. Other platforms are ignored. In the SOP, where no alternatives are given to the fixed routes, it is assumed that all corresponding platforms included in the subset are visited. A sequence number is coupled to each platform, where the PSV sails from the depot to platforms in accordance with the corresponding sequence numbers. Figure 5-1 illustrates how a given route and the corresponding facilities and sequence numbers are coupled. As one can see from the figure, a route is represented as a set of platforms arranged in a specific order. From this arrangement a coupling can be drawn between a platforms and the corresponding sequence of visitation, as

$$\mathbf{Platform} = \mathbf{Platform}(\mathbf{Sequence})$$

By using this relationship, a given route with n platforms can be transformed to useful input data for the mathematical model, which is presented as a subset of platforms on the form

$$\textbf{Subset of platforms} = \{\mathbf{platform(1)}, \dots, \mathbf{platform(n)}\}$$

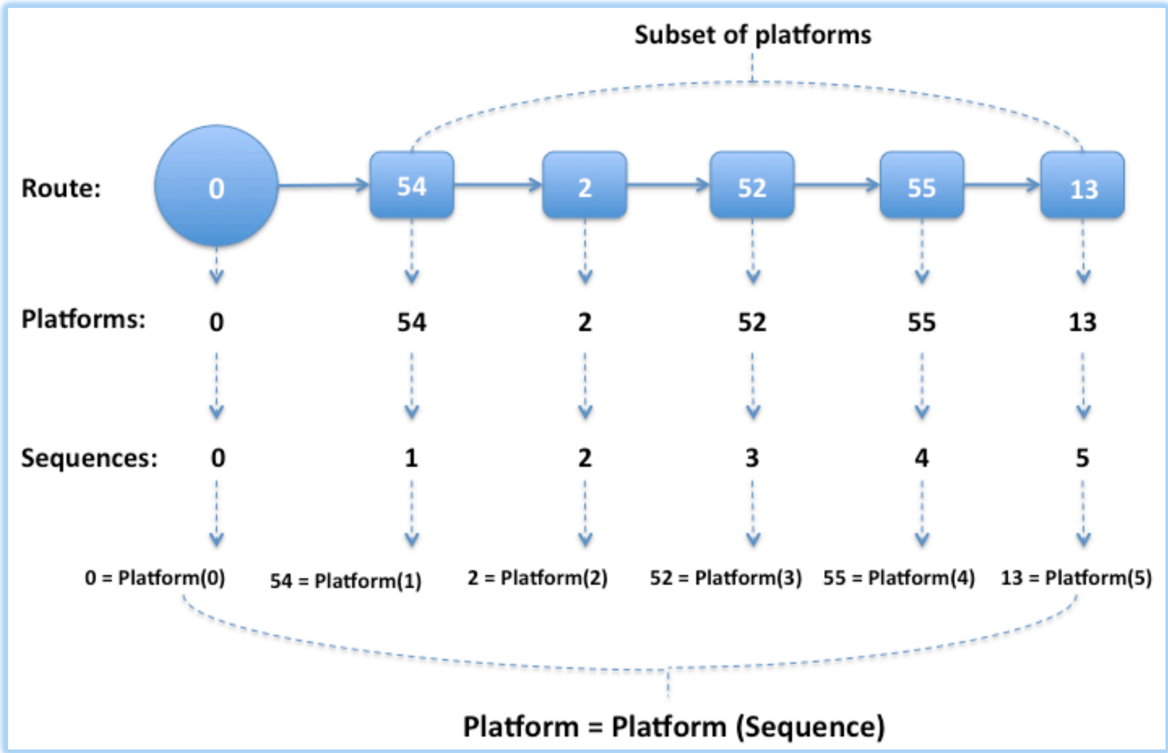

Figure 5-1: *The SOP relationship between routes, platforms and sequence numbers*

Note that the depot is always coupled to sequence number 0, as the PSV begins its journey here. It is assumed that no extra considerations arises from a change to the route in a given period in the sense that all stated platforms will be visited even if orders are not served at all stops. With these assumptions the SOP model does not need any additional route constraints.

Orders

Deliveries and pickups are made according to order demand for the yielding platforms. As a departure and its belonging route only consist of a subset of platforms that are visited, only the orders corresponding to the platforms in the subset can be served. But as vessel capacity restricts the problem, not all orders of concern are guaranteed served even if they correspond to the platforms visited. Orders beyond the platforms visited are ignored in the matter of demand service, as they do not affect the outcome in the present period. However, all orders are of matter when calculating parameters like costs for each period, as they are to serve as a basis for further analysis when route operations are proposed altered.

Costs

To find the best way of allocating orders in a given departure, a cost is introduced to represent the inconvenience of delay. This cost may depend on the priority and size of the order, whether it is a pickup or delivery, and length of delay. The SOP is a minimisation problem, where the objective function minimises the inconvenience costs incurred in one period. To serve as a basis when adding flexibility or dynamics, all orders not served should inquire lateness costs. But in the one-period SOP problem, the only costs of importance are the ones coupled to platforms visited during the given period, as they are the ones attempted minimised when considering the orders to serve.

5.2.2 The SOP model formulation

This section presents all notations and the mathematical formulation for the supply order problem with completely fixed routes. In the matter of notation, subscripts and decision variables are represented as lower-case letters, and parameters and sets are represented as capital letters. All is formulated for a given, single period.

Sets

P	$P = \{1, \dots, \bar{P}\}$	Set of all platforms ($\bar{P}$ platforms in total)
P^T	$P^T \subseteq P$	Subset of platforms in the given route
K	$K = \{0, \dots, \lvert P^T \rvert\}$	Set of sequence numbers coupled to facilities in the given route by $p = p(k)$ for $k \in K$, and $\{0\}$ is coupled to the depot.
O_p	$p \in P$	Set of orders for platform p
${O_p}^D$	$p \in P, {O_p}^D \subseteq O_p$	Set of delivery orders for platform p
${O_p}^P$	$p \in P, {O_p}^P \subseteq O_p$	Set of pickup orders for platform p

Parameters

K		The vessel deck capacity in square meters
Q_o	$p \in P, o \in O_p$	Demand requirement for order o in square meters
${C_o}^L$	$p \in P, o \in O_p$	Lateness cost due to an order o not being served

Variables

u_o	$p \in P^T, o \in O_p$	1 if order o is served, 0 otherwise
l_p	$p \in P^T$	Load on board the vessel leaving platform p

Objective function

$$\min \sum_{p \in P^T} \sum_{o \in O_p} {C_o}^L \cdot (1 - u_o) \tag{5.0}$$

The objective function (5.0) minimises the costs. The cost C_o is a cost estimated for the given order o and it is added for all the orders not served in the present period.

Constraints

$$l_0 = \sum_{p \in P^T} \sum_{o \in {O_p}^D} Q_o u_o \tag{5.1}$$

$$l_{p(k)} = l_{p(k-1)} - \sum_{o \in {O_{p(k)}}^D} Q_o u_o + \sum_{o \in {O_{p(k)}}^P} Q_o u_o \qquad k \in K \tag{5.2}$$

$$0 \leq l_p \leq K \qquad p \in P^T, \{0\} \tag{5.3}$$

$$u_o \in \{0,1\} \qquad p \in P^T, o \in O_p \tag{5.4}$$

Constraint (5.1) is the initiation of the load for the departure, setting the load going out from the depot equal to the total delivery quantity. In constraints (5.2), the load is updated for each platform visited. The load going out from a current platform is thus equal to the load coming in to the platform minus the net demand for the platform. The net demand includes both delivery pickup quantities served at the respective platform, where the deliveries are added and pickups are subtracted to update the current load. The notation $p(k)$ ensures the movement between platforms in the sequence given by the route, so platform p is visited as number k in the route. The total load needs to be a non-negative number restricted by vessel capacity at each node, at all time. Constraints (5.3) make sure of this this and guarantee that the vessel load never exceeds capacity. Constraints (5.4) define the binary variables u_o stating whether an order o is served or not.

5.3 Level 2: The Supply Order Problem with Flexible Routes (SOP-FR)

When allowing the exclusion of platforms for the given, fixed routes most of the assumptions stated for simple SOP still yield, except for some adjustments. The new and customized assumptions are presented in the following, before the mathematical SOP-FR model is formulated. Concerning notation, some additions and changes are needed when allowing the exclusion of platforms for a given route. All notations corresponding to the mathematical model, both the previous from Section 5.2 and additions, are presented to make the model more readable.

5.3.1 Additional SOP-FR assumptions

The model is still formulated for one period, as the relevant input is the route scheduled for the corresponding departure. As decisions are made concerning which platforms in the given route that should be visited, the SOP-FR becomes to optimally decide which platforms to include and the belonging orders to serve. The vessel departs from the port and follows a route adjusted in the model, visiting the platforms worth of service based on orders requested and distances travelled.

Facilities and routes

In the one-period problem there is still only one route travelled, which is the relevant input given as a list of platforms that can be visited. Only the subset of platforms for the single period is considered. When introducing flexible routes, an alternative to exclude one or several platforms from the subset of platforms given is allowed. It is no longer assumed that all platforms are visited, but no additional platforms beyond the given subset are allowed. Deliveries and pickups are still made according to orders and the vessel capacity, but at this instance the actual platforms in the route being serviced is taken into account as well. It is assumed that a platform will not be visited as long as no orders are served at the stop.

Sequence numbers are still coupled to platforms similar to the level 1 problem, and the predetermined routes currently yielding at Petrobras restrict the voyages. As the option to exclude platforms from a given route is present, not all sequence numbers are necessarily a part of the route conducted in the end, though. Even so, the PSV is planned to sail from the depot to the platforms coupled to sequence numbers in increasing order. Nodes will be used in the model formulation, to make to model more readable. However, nodes and sequence numbers have the exact same effect and coupling to platforms. Figure 5-2 illustrates how a given route and the corresponding platforms and nodes are coupled.

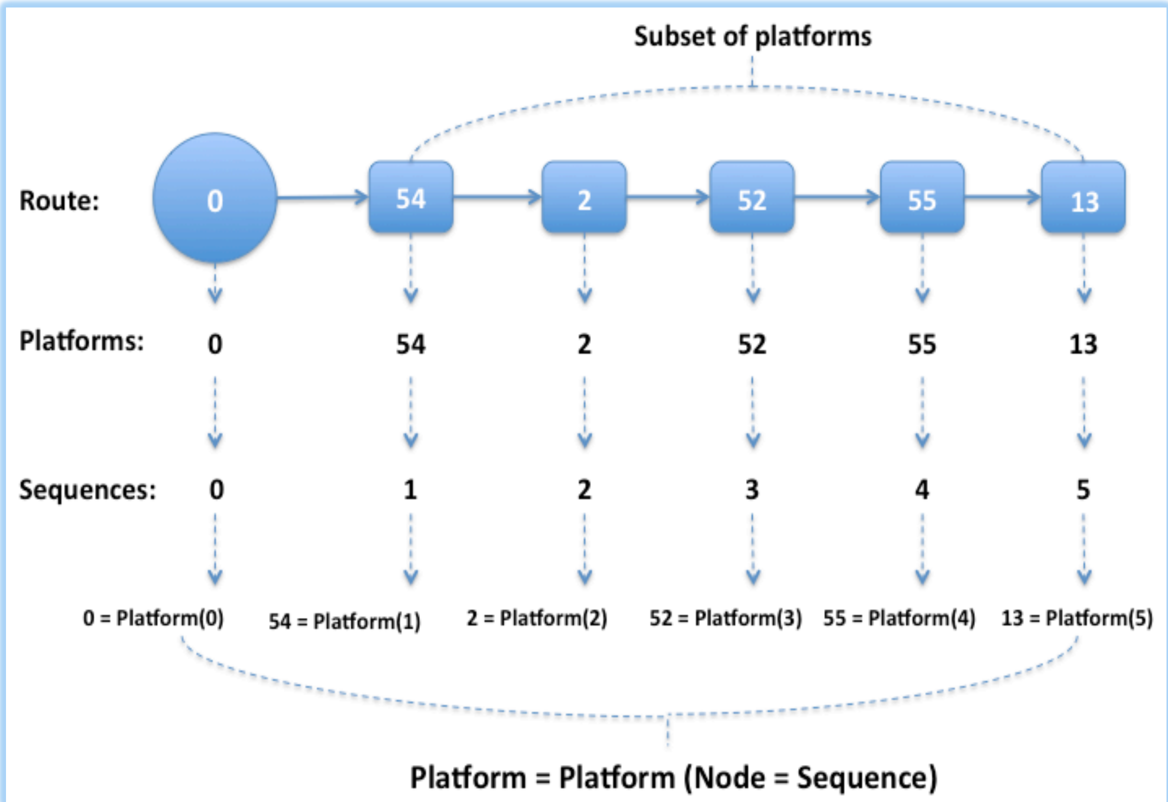

Figure 5-2: *The SOP-FR relationship between routes, platforms and nodes (sequence numbers)*

As seen from Figure 5-2, a route is represented as a set of n platforms visited in a specific order, where the coupling between platforms and node numbers are similar as in the level 1 coupling between platforms and sequence numbers. This coupling is given as,

$$\mathbf{Platform} = \mathbf{Platform}(\mathbf{Node})$$

By using this relationship, a given route can be transformed to useful input data for the mathematical model, which is presented as a subset of platforms on the form

$$\mathbf{Subset\ of\ platforms} = \{\mathbf{platform}(\mathbf{1}), \dots, \mathbf{platform}(\mathbf{n})\}$$

Note however, that there is a slight difference between Figure 5-1 and Figure 5-2 showing the same relationship in the different levels. The depot is now coupled to two nodes, 0 and $n+1$, representing the sequence numbers. Each of these couplings represents the starting and ending of the journey, respectively. Two separate nodes have to be used in this setting as the PSV always travels toward increasing node numbers in level 2, due to their relationship to sequence numbers. Hence, two nodes are necessary in forcing both start up and completion at the depot.

Orders

As for level 1, only the orders than can be served are the ones requested from platforms in the subset. But due to vessel capacity and the additional objective of minimising the distances travelled, not all orders are guaranteed served even if they correspond to the subset of platforms in the given period.

Costs

The cost elements are still only included in the objective function. When adding the alternative to exclude platforms from the fixed and predetermined routes, the distance travelled is a part of the objective as well. As the distance travelled is related to the service of orders, savings in distance is balanced against the inconvenience of delay that arises when orders are not served. Ultimately, the problem is to find the most optimal balance between these two contradicting cost elements, namely distances travelled and order delay. And for costs concerning travel distance, only the variable sailing cost given per kilometre travelled need to be taken into consideration, as it is assumed that all scheduled departures and hence the planned use of PSVs is still conducted.

5.3.2 The SOP-FR model formulation

This section presents all notations and the mathematical formulation for the SOP-FR where flexibility is added to the fixed and predetermined routes. In the matter of notation, subscripts and decision variables are represented as lower-case letters, and parameters and sets are represented as capital letters. All is formulated for a given, single period.

Sets

P	$P = \{1, \ldots, \bar{P}\}$	Set of all platforms ($\bar{P}$ platforms in total)
P^T	$P^T \subseteq P$	Subset of platforms in the given route

N	$N = \{0, \dots, \overline{P^T} + 1\}$	Set of nodes coupled to facilities in the given route, by $p = p(i)$ for $i \in N$. $\{0\}$ and $\{\overline{P^T} + 1\}$ represent the depot, where $\overline{P^T}$ is the number of platforms in the given route
N^F	$N^F = \{1, \dots, \overline{P^T}\} \subseteq N$	Set of nodes coupled to platforms by $p = p(i)$ for $i \in N$
N^L	$N^L = \{0, \dots, \overline{P^T}\} \subseteq N$	Set of leaving-nodes coupled to facilities, by $p = p(i)$ for $i \in N$
O_p	$p \in P$	Set of orders for platform p
${O_p}^D$	$p \in P, {O_p}^D \subseteq O_p$	Set of delivery orders for platform p
${O_p}^P$	$p \in P, {O_p}^P \subseteq O_p$	Set of pickup orders for platform p
A	$(i,j) \in A, i,j \in N, i < j$	Set of arcs, from node i to node j

Parameters

K		The vessel deck capacity in square meters
Q_o	$p \in P, o \in O_p$	Demand requirement for order o in square meters
${C_o}^L$	$p \in P, o \in O_p$	Lateness cost due to an order o not being served
C^S		Sailing cost per distance travelled
D_{ij}	$(i,j) \in A$	Sailing distance from node i to node j

Variables

u_o	$p \in P, o \in O_p$	1 if order o is served, 0 otherwise
l_i	$i \in N^L$	Load on board the vessel leaving node i
v_i	$i \in N^F$	1 if node i is served, 0 otherwise
x_{ij}	$(i,j) \in A$	1 if the vessel travels from node i to j, 0 otherwise

Objective function

$$minimize \sum_{p\in P^T}\sum_{o\in O_p} {C_o}^L(1-u_o)+\sum_{(i,j)\in A} C^S D_{ij}x_{ij} \tag{5.5}$$

The objective function (5.5) minimises the total cost attained in a given period. The first term represents the punishment costs due to the lateness associated with orders not being served, while the second term calculates the travelling costs corresponding to the platforms visited in the present period.

Constraints

$$\sum_{j\in N} x_{0,j} = 1 \tag{5.6}$$

$$\sum_{i\in N} x_{i,\overline{P^T}+1} = 1 \tag{5.7}$$

$$\sum_{j\in N} x_{ij} = v_i \qquad i\in N^F \tag{5.8}$$

$$\sum_{i\in N} x_{ij} = v_j \qquad j\in N^F \tag{5.9}$$

$$v_i \geq u_o \qquad i\in N^F, o\in O_{p(i)} \tag{5.10}$$

$$l_0 = \sum_{i\in N^F}\sum_{o\in {O_{p(i)}}^D} Q_o u_o \tag{5.11}$$

$$0 \leq l_i \leq K \qquad i\in N^L \tag{5.12}$$

$$l_j \geq l_i - \sum_{o\in {O_{p(j)}}^D} Q_o u_o + \sum_{o\in {O_{p(j)}}^P} Q_o u_o - (1-x_{ij})K \qquad i\in N^L, j\in N^F, i<j \tag{5.13}$$

$$x_{ij} \in \{0,1\} \qquad (i,j)\in A \tag{5.14}$$

$$u_o = \{0,1\} \qquad p\in P^T, o\in O_p \tag{5.15}$$

$$v_i = \{0,1\} \qquad i\in N^F \tag{5.16}$$

Constraints (5.6)-(5.9) are degree constraints. Constraints (5.6) and (5.7) make sure that the route starts and ends at the depot, where the depot is travelled from and to exactly once at the beginning and end of the route respectively. No other visitations to the depot are performed. Constraints (5.8) and (5.9) state that platforms are visited once, either for pickup, delivery or simultaneous pickup and delivery, given they are served in the present period. Otherwise a platform is not visited. Constraints (5.10) ensure that served nodes associated with platforms are visited, by forcing a node to be visited as long as at least one delivery and/or pickup service occurs for the corresponding platform. Constraint (5.11) initializes the outgoing load from port to be equal to the total demand for all nodes served with deliveries in the given period. The total load needs to be a non-negative number restricted by vessel capacity at each node, at all time. Constraints (5.12) make sure of this this and guarantee that the vessel load never exceeds its capacity. Constraints (5.13) control the pickup and delivery load in the vessel after a node is visited, as they define l_j in terms of l_i whenever node j is visited immediately after node i. When pickup and delivery are done simultaneously, the outgoing load is equal to the ingoing load with the delivery and pickup performed subtracted and added, respectively. Otherwise, only delivery is subtracted or pickup is added. Constraints (5.14) - (5.16) define binary conditions.

5.4 Level 3: The Supply Order Problem with Dynamic Routes (SOP-DR)

The route travelled in each departure is made dynamically in model level 3. To incorporate dynamics, a single vessel routing problem has to be solved for each departure. In doing so, the previous stated assumptions for the SOP and SOP-FR are completely altered. These alterations and new assumptions are presented below, before the mathematical models for the SOP-DR are formulated. A route is made dynamic in the sense that for a yielding departure a set of orders in need of service is given, and corresponding platforms visited and the route travelled are made accordingly. The problem at this instance is not just to decide which orders to serve and platforms to exclude, but it also includes optimally deciding which platforms to visit and how they should be served considering all platforms.

5.4.1 Additional SOP-DR assumptions

A single departure is no longer coupled to a period as in previous model levels. Each departure is optimized, so the previous schedules and time slots used when routes are fixed and predetermined are no longer yielding. The mathematical SOP-DR is formulated for a single departure seen in isolation, where elements concerning time and periods are further discussed in Chapter 6.

For a single journey one vessel still departs from the depot and follows a route which is to be determined in using the models below. Due to capacity constraints and the orders given situations may arise where it is more convenient to visit a given platform two times during a departure. When two visits are performed, pickup and delivery demands are served separately. Since Petrobras currently only operates with only one visitation per platform for a given departure, using this assumption when making the routes dynamically should still be explored. Consequently two sublevels of model level 3 are presented. The one-visit rule currently yielding for Petrobras still applies for the SOP-DR-1, where the problem is to optimally decide which of and in what sequence the platforms corresponding to the requested orders for a period should be serviced. The SOP-DR-2 takes the dynamics a step further, where platforms in a yielding route is allowed a second visit and the routing becomes more complex.

Facilities and routes

In the SOP-DR, no subset of platforms is given and all platforms corresponding to the given set of orders are evaluated. Platforms may require both delivery and pickup, or delivery or pickup only. During only one visit to a platform, which may be the case in both sublevels, pickups and deliveries are done simultaneously given that both occur. For the SOP-DR-2 a platform can be visited twice if pickup and delivery are done separately, due to capacity constraints and the demand requested.

A node formulation is presented in generating the route for a single departure. This is especially important when allowing two visits per platform, as for the SOP-DR-2. One node is coupled to each platform including the depot in the SOP-DR-1, while in the SOP-DR-2 two nodes are coupled to each platform. As no sequence numbers are coupled to platforms in model level 3, the models are formulated in a way that allows the PSV to move towards both increasing and decreasing node numbers. Figure 5-3 and Figure 5-4 illustrates how nodes and platforms are coupled.

As illustrated in Figure 5-3, when only one node is coupled to each platform, the number of nodes evaluated in the model is equal to the total number of platforms n. The coupling between a platform and a node is presented as

$$\mathbf{Platform} = (\mathbf{Platform}, \quad \mathbf{Node})$$

Two nodes coupled to the depot are necessary, where node 0 represent start-up while $n + 1$ represent completion.

Illustrated in Figure 5-4, when two nodes are coupled to a platform, the number of nodes evaluated in the model is the doubled compared to the total number of platforms ($2n$). The first set of nodes corresponds to deliveries, while the second set is for pickups. It is assumed that neither the delivery demands nor the pickup demands served for a platform can be split between two visits, meaning that all delivery orders or all pickup orders served to a given platform must be performed in one visit. This should be a safe assumption, as there exists no reason to save a delivery order for a second visit or to pick up an order on the first one when planning a second visit as long as the only restricting element is the capacity on board the vessel. Hence, the coupling between a platform and the corresponding pickup and delivery nodes is

$$\mathbf{Platform} = (\mathbf{Platform}, \quad \mathbf{Delivery\ node}, \quad \mathbf{Pickup\ node})$$

As for the single-node formulation, two nodes are coupled to the depot as 0 and $2n + 1$ for start-up and completion respectively.

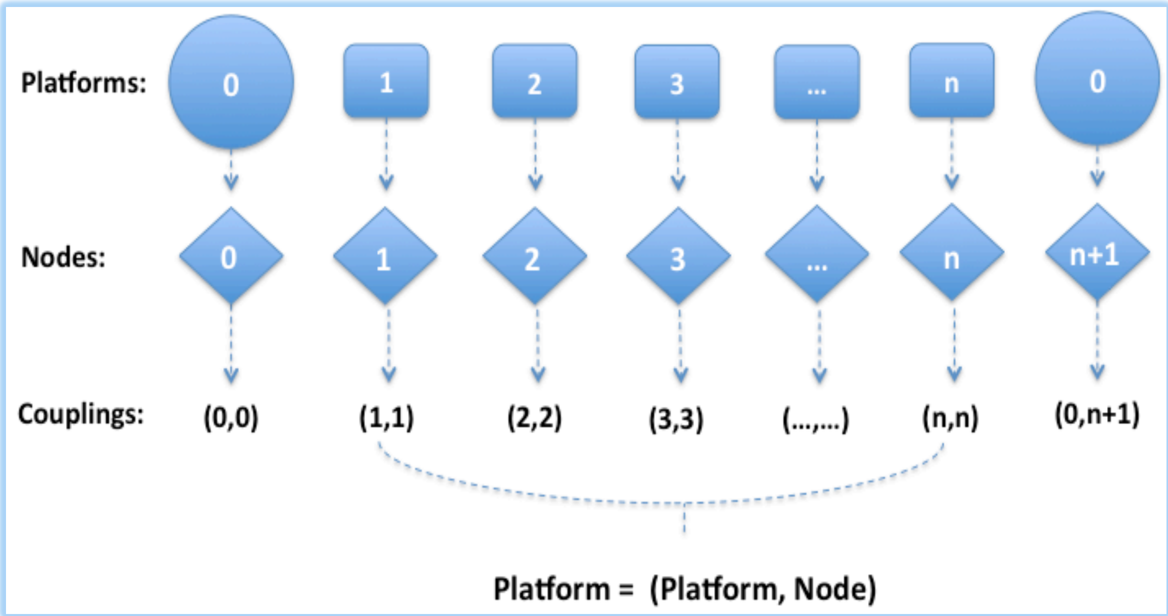

Figure 5-3: *The SOP-DR-1 relationship between platforms and nodes*

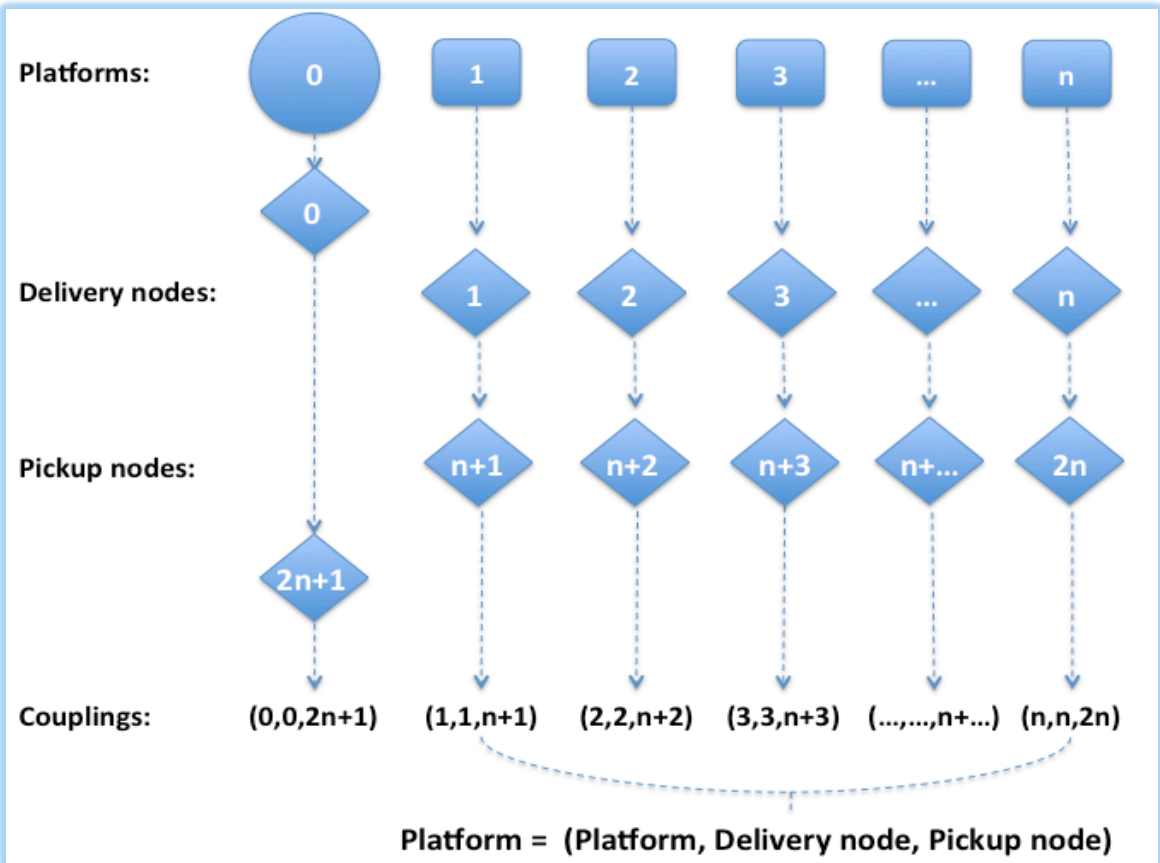

Figure 5-4: *The SOP-DR-2 relationship between platforms and nodes*

When both deliveries and pickups are served to a given platform, the services may be provided either separately or simultaneously. In both situations, the mathematical SOP-DR-2 model is formulated such that both nodes are visited. The only difference is that when separate services occur other platforms are visited in between the two, whilst for simultaneous delivery and pickup the pickup node is served directly after the delivery node. In the latter situation, no additional distances are travelled. Figure 5-5 illustrates how separate and simultaneous pickup and delivery to a platform are conducted when nodes are concerned.

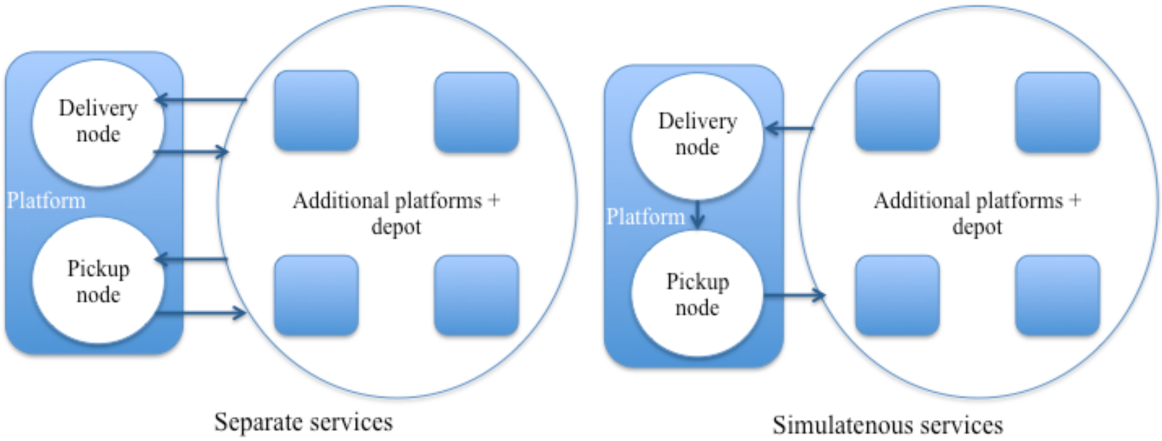

Figure 5-5: *Separate versus simultaneous pickup and delivery*

Orders

It is still assumed that a platform places at most one pickup and one delivery request per period and that the difference in both size and number combined results in pickups being one third compared to deliveries in the long run. But in the case for one departure seen in isolation, a pickup for a given platform may be larger than a delivery, giving room for a second visit to the yielding platform.

In previous notations, orders were coupled to platforms requiting them. In level 3 however, where a node representation is used, orders are coupled to nodes in stead. This is especially important when two nodes are coupled to each platform, as in level 3.1. Deliveries belong to the first set of nodes, namely delivery nodes, whilst deliveries belong to the pickup node set.

Costs

The cost elements are still only included in the objective function, as the objective is to minimize costs obtained in a given departure. When routes are made dynamically the objective should target the distances travelled in addition to order service. Hence, the problem is to find the optimal balance between the costs occurred due to travel distances and the inconvenience of order delay. As a single journey of a PSV in conducted in a given period, only the variable sailing cost given per kilometre is considered when the distance travelled is addressed.

5.4.2 The SOP-DR-1 model formulation

This section presents all notations and the mathematical formulation for the supply order problem with dynamic routes, where only one visit to a platform is allowed. In the matter of notation, subscripts and decision variables are represented as lower-case letters, and parameters and sets are represented as capital letters. All is formulated for a single departure.

Sets

V	$V = \{0, \dots, \bar{P}+1\}$	Set of all nodes including the depot $\{0\}$ and $\{\bar{P}+1\}$, where $\bar{P}$ is the number of platforms
V^F	$V^F = \{1, \dots, \bar{P}\} \subseteq V$	Set of nodes coupled to platforms (offshore facilities)
O_i	$i \in V^F$	Set of orders for node i
${O_i}^D$	$i \in V^F, {O_i}^D \subseteq O_i$	Set of delivery orders for node i
${O_i}^P$	$i \in V^F, {O_i}^P \subseteq O_i$	Set of pickup orders for node i
A^1	$(i,j) \in A^1, i,j \in V, i \neq j$	Set of arcs, from node i to node j

Parameters

K		The vessel deck capacity in square meters
Q_o	$i \in V^F, o \in O_i$	Demand requirement for order o in square meters
${C_o}^L$	$i \in V^F, o \in O_i$	Lateness cost due to an order o not being served
C^S		Sailing cost per distance travelled
D_{ij}	$(i,j) \in A^1$	Sailing distance from node i to node j

Variables

u_o	$i \in V^F, o \in O_i$	1 if order o is served, 0 otherwise
l_i	$i \in V$	Load on board the vessel leaving node i
v_i	$i \in V^F$	1 if node i is served, 0 otherwise
x_{ij}	$(i,j) \in A^1$	1 if the vessel travels from node i to j, 0 otherwise

Objective function

$$minimize \sum_{i \in V^F} \sum_{o \in O_i} {C_o}^L (1 - u_o) + \sum_{(i,j) \in A^1} C^S D_{ij} x_{ij} \tag{5.17}$$

The objective function (5.17) minimises the total cost occurred for a given period. The first term represents the punishment costs due to the lateness associated with orders not being served, while the second term calculates the travelling costs corresponding to the platforms visited.

Constraints

$$\sum_{j \in V} x_{0,j} = 1 \tag{5.18}$$

$$\sum_{i \in V} x_{i,\bar{P}+1} = 1 \tag{5.19}$$

$$\sum_{j \in V} x_{ij} = v_i \qquad i \in V^F \tag{5.20}$$

$$\sum_{i \in V} x_{ij} = v_j \qquad j \in V^F \tag{5.21}$$

$$v_i \geq u_o \qquad i \in V^F, o \in O_i \tag{5.22}$$

$$l_0 = \sum_{i \in V^F} \sum_{o \in {O_i}^D} Q_o u_o \tag{5.23}$$

$$0 \leq l_i \leq K \qquad i \in V \tag{5.24}$$

$$l_j \geq l_i - \sum_{o \in {O_j}^D} Q_o u_o + \sum_{o \in {O_j}^P} Q_o u_o - (1 - x_{ij})K \qquad (i,j) \in A^1 \tag{5.25}$$

$$\sum_{(i,j) \in S} x_{ij} \leq |S| - 1 \qquad S \subset V^F, |S| \geq 2 \tag{5.26}$$

$$x_{ij} \in \{0, 1\} \qquad (i,j) \in A^1 \tag{5.27}$$

$$u_o = \{0, 1\} \qquad i \in V^F, o \in O_p \tag{5.28}$$

$$v_i = \{0, 1\} \qquad i \in V^F \tag{5.29}$$

Constraints (5.18)-(5.21) are degree constraints. Constraints (5.18) and (5.19) make sure that the route starts and ends at the depot, where the depot is travelled from and to exactly once at the beginning and end of the route, respectively, in the single period. No other visitations to the depot are performed. Constraints (5.20) and (5.21) state that the node associated with a platform is visited once, either for pickup, delivery or simultaneous pickup and delivery, given that the node is to be served in the given period. Otherwise the node is not visited. Constraints (5.22) ensure that served nodes associated with platforms are visited. More than one pickup and/or delivery may be served for a platform in a given period, and constraints (5.22) forces a node to be visited as long as at least one delivery service occurs for the corresponding platform. Constraint (5.23) initializes the outgoing load from port to be equal to the total demand for all nodes served with deliveries in the given period. The total load needs to be a non-negative number restricted by vessel capacity at each node, at all time. Constraints (5.24) make sure of this this and guarantee that the vessel load never exceeds its capacity. Constraints (5.25) control the pickup and delivery load in the vessel after a node is visited; as they define l_j in terms of l_i whenever node j is visited immediately after node i. When pickup and delivery are done simultaneously, the outgoing load is equal to the ingoing load with the delivery and pickup performed subtracted and added, respectively. Otherwise, only delivery is subtracted or pickup is added. Constraints (5.26) are the standard subtour elimination constraints (Dantzig et al., 1954), as constraints (5.25) are not sufficient to eliminate subtours for when the vessel load vary monotonically. As an example, subtours could be created over subsets S for which the sum of delivery demand is equal to the sum of pickup demand. Constraints (5.27) - (5.29) define binary conditions.

5.4.3 The SOP-DR-2 model formulation

This section presents all notations and the mathematical formulation for the supply order and routing problem with pickup and delivery when allowing two visits per platform. Subscripts and decision variables are represented as lower-case letters, and parameters and sets as capital letters. All is formulated for a single departure.

Sets

W	$W = \{0, \dots, 2\bar{P} + 1\}$	Set of all nodes. Two nodes i and $i + \bar{P}$ are coupled to a platform and $\bar{P}$ is the number of platforms
W^F	$W^F = \{1, \dots, 2\bar{P}\} \subseteq W$	Set of nodes coupled to platforms (offshore facilities)
W^D	$W^D = \{1, \dots, \bar{P}\} \subseteq W$	Set of delivery nodes coupled to platforms
W^P	$W^P = \{\bar{P} + 1, \dots, 2\bar{P}\} \subseteq W$	Set of pickup nodes coupled to platforms
O_i	$i \in W^F$	Set of orders for node i
A^2	$(i,j) \in A^2, i,j \in W, i \neq j$	Set of arcs, from node i to node j

Parameters

K		The vessel deck capacity given in square meters
Q_o	$i \in W^F, o \in O_i$	Demand requirement for order o in square meters
${C_o}^L$	$i \in W^F, o \in O_i$	Lateness cost due to an order o not being served
C^S		Sailing cost per distance travelled
$\bar{D}_{ij}$	$(i,j) \in A^2$	Extended distance matrix that copes with the possibility of platforms being visited twice.

Variables

u_o	$i \in W^F, o \in O_i$	1 if order o is served, 0 otherwise
l_i	$i \in W$	Load on board the vessel leaving node i
v_i	$i \in W^F$	1 if node i is served, 0 otherwise
x_{ij}	$(i,j) \in A^2$	1 if the vessel travels from node i to j, 0 otherwise

Objective function

$$minimize \sum_{i \in W^F} \sum_{o \in O_i} {C_o}^L (1 - u_o) + \sum_{(i,j) \in A^2} C^S \overline{D}_{ij} x_{ij} \tag{5.30}$$

The objective function (5.30) minimises the total cost occurred for a given period. This includes both traveling costs and the punishment costs due to the lateness associated with orders not being served.

Constraints

$$\sum_{j \in W} x_{0,j} = 1 \tag{5.31}$$

$$\sum_{i \in W} x_{i,2\bar{P}+1} = 1 \tag{5.32}$$

$$\sum_{j \in W} x_{ij} = v_i \qquad i \in W^F \tag{5.33}$$

$$\sum_{i \in W} x_{ij} = v_j \qquad j \in W^F \tag{5.34}$$

$$v_i \geq u_o \qquad i \in W^F, o \in O_i \tag{5.35}$$

$$l_0 = \sum_{i \in W^D} \sum_{o \in O_i} Q_o u_o \tag{5.36}$$

$$0 \leq l_i \leq K \qquad i \in W \tag{5.37}$$

$$l_j \geq l_i - \sum_{o \in O_j} Q_o u_o - (1 - x_{ij}) K \qquad i \in W, j \in W^D, i \neq j \tag{5.38}$$

$$l_j \geq l_i + \sum_{o \in O_j} Q_o u_o - (1 - x_{ij}) K \qquad i \in W, j \in W^P, i \neq j \tag{5.39}$$

$$\sum_{i,j \in S} x_{ij} \leq |S| - 1 \qquad S \subset W^F, |S| \geq 2 \qquad (5.40)$$

$$x_{ij} \in \{0, 1\} \qquad (i, j) \in A^2 \qquad (5.41)$$

$$u_o = \{0, 1\} \qquad i \in W^F, o \in O_i \qquad (5.42)$$

$$v_i = \{0, 1\} \qquad i \in W^F \qquad (5.43)$$

Constraints (5.31) – (5.34) are degree constraints. Constraints (5.31) and (5.32) make sure that the route starts and ends at the depot, where the depot is travelled from and to exactly once at the beginning and end of the route, respectively, in the present period. No other visitations to the depot are performed. Constraints (5.33) and (5.34) state that the node associated with each platform is visited once, either for delivery or for simultaneous pickup and delivery, given that the node is to be served in the present period. Otherwise the node is not visited. Constraints (5.35) ensure that served nodes associated with platforms are visited, as they force a node to be visited as long as at least one order service occurs for the corresponding platform. Constraint (5.36) initializes the outgoing load from port to be equal to the total demand for all nodes served with deliveries in the given period. The total load needs to be a non-negative number restricted by vessel capacity at each node, at all time. Constraints (5.37) make sure of this this and guarantee that the vessel load never exceeds its capacity. Constraints (5.38) and (5.39) control the load on board the vessel after a node is visited; as they define l_j in terms of l_i whenever j is visited immediately after i. In constraints (5.38), i is the first node associated with platform p, where delivery may be performed. The outgoing load is equal to the ingoing load with the delivery performed subtracted. Constraints (5.39) works in a similar matter, where node $i + n$ is the second node associated with platform p. For these nodes, the outgoing load is equal to the ingoing where the pickup performed is added. Constraints (5.38) and (5.39) also eliminate sub-tours when pickup and delivery are done simultaneously. Constraints (5.40) are the standard subtour elimination constraints (Dantzig et al., 1954), as constraints (5.38) and (5.39) are not sufficient to eliminate subtours for when the vessel load vary monotonically. As an example, subtours could be created over subsets S for which the sum of delivery demand is equal to the sum of pickup demand. Constraints (5.41) - (5.43) define binary conditions.

5.5 The SOP with a rolling horizon

To illustrate how the supply order problem works in a longer time frame, the rolling horizon principle is explained. The explanation incorporates the supply order problem as formulated at level 1 only, where routes are fixed and pre-determined. The same principal when concerning levels 2 and 3 works in a similar manner, where the routing part is taken into account as well. Level 1 is used in this setting however, as the intention is to explain how the supply order problem works in practice, and not the routing part. As routes for level 1 serves as the basis, periods are used in this setting. The model will be tested for the one-period problem first and then expanded to go over several days with a rolling horizon. Firstly, assumptions are stated, before an illustrative example tries to explain the concept of a rolling horizon.

5.5.1 Additional SOP rolling horizon assumptions

The model is solved for one departure at a time; so it is the same for each and all the assumptions stated in sections 5.1 and 5.2 previously hold. Some changes are however done when implementing the model to be able to handle different routes and periods, and to treat the orders dynamically. A loop enables the program to move automatically from one period to the next until stopped by a given criterion concerning the number of periods.

Routes

One period at a time is still considered, but now the route changes for different departures. There are several departures in a week, where the number of departures depends on the weekday, and where each departure has distinctive combinations of platforms and sequences. Each departure is seen as a separate period, where new input is given when the loop moves from one period to the next. It is assumed that the same schedule is used for all weeks; so specific weekdays in different weeks have the same departures. For instance, the routes are the same on all Mondays.

Departures

Each departure is in this case considered as a single period. The time of each departure and the number of departures currently depend on the weekday, and differ accordingly for Petrobras. Time wise, only the arranged order for when the different periods are conducted plays a role, which implies that for the first week route 1 belonging to period 1 is conducted before route 1 belonging to period 2, etc. In doing so, all periods are viewed separately, where the only concern is the number of periods during a week.

Orders

A new list of orders is received on a daily basis. The difference now is that the orders from previous periods that are not served yet should be a part of the orders that are to be assigned in the current problem. This is implemented with different dynamic parameters, so the sets of orders are updated for each period. The list of orders relevant for each departure consists of both the new orders and the undistributed orders carried over from previous periods.

As approximately 50 % of all orders made are defined as emergencies, and thereby served with express if the delay limit is reached, it is assumed that an order request is made independent of the fixed route and departure schedule. This means that the different platforms request supply when needed, without considering when the next departure servicing the corresponding platform will take place. At the same time, the platform requesting has knowledge about the different departures and platform services when making a request, and even so would want the supply to be delivered as quickly as possible.

Costs

The inconvenience cost used in the objective function is increasing to ensure that the older orders are given a higher priority. The intention of the inconvenience cost is to guarantee that as many orders as possible and the most valuable ones are served each period. Valuable in this case, being related to factors like departures of delay, size of orders, the order being pick or delivery etc. The inconvenience cost is added to an order for all periods prior to service, independent of the corresponding platform being visited or not.

5.5.2 SOP rolling horizon example

An example of how the model with a rolling horizon concept works in practice is presented below with accompanying illustrations. For time t, there are two two order lists; one for pickups and one for deliveries. Each order in the two lists consists of orders numbers o and a corresponding platform p linked together as $o(p)$. The route includes five platforms. The orders and the route are taken into the model, along with data on demand quantities for the orders and vessel capacity, and the model is optimised for the current period t. Then, the loop continues to the next period $t + 1$, where new orders become known. The new orders are combined with the remaining orders from t to comprise the orders that are input for the model at $t + 1$.

For simplicity in the example, the vessel capacity is set to 50. Information concerning orders being pickups or deliveries and the order sizes are given below the corresponding orders in the tables.

Period t:

Orders:	4(2)	20(58)	11(52)	12(28)	2(54)	15(61)	7(13)	23(55)
Delivery D / Pickup P:	D	D	P	P	D	P	D	D
Demands:	15	28	12	8	10	10	17	18
Route:	54	2	52	55	13			
Served orders:	2(54)	11(52)	23(55)	7(13)				
Remaining orders:	4(2)	20(58)	12(28)	15(61)				
Total costs:	C(4)							

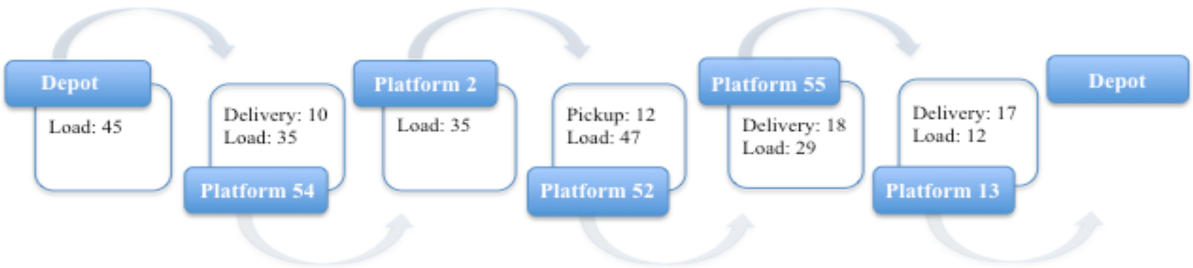

Figure 5-6: *Model solution period t*

The orders served belong to the platforms visited in the route. However, at period t order 4(2) is not delivered even though platform 2 is in the route, due to capacity restrictions. The load going out from the depot is 45, so the additional demand from platform 2 of 15 would exceed the capacity on the vessel. The orders can not be split, so the entire order is left behind. Order 4(2) is in this case chosen among all orders possible of service, as it corresponds to the smallest possible demand quantity not being served in the period. Hence, at this instance the lateness costs is dependent on the size of the order. Different cost functions, both dependent and independent on the order size and other factors, will be discussed in Chapter 7. All other orders for visited platforms are served, so a better solution could not be found when the cost is size dependent only. Order 4(2) gets an updated cost after this period, as shown as C(4), where C is this case is the result of a calculated cost function for the given order, comprised of order size and a constant. The orders for platforms 54, 52, 55 and 13 do not get any cost added since the platforms are not in the route. All the unserved orders after period t are saved and included in the order list for time t+1.

Period t+1:

Remaining orders:	4(2)	20(58)	12(28)	15(61)				
New orders:	1(5)	8(58)	17(9)	21(17)				
Orders:	4(2)	20(58)	12(28)	15(61)	1(5)	8(58)	17(9)	21(17)
Delivery D / Pickup P:	D	D	P	P	D	P	D	D
Demand:	15	28	8	10	13	14	22	19
Route:	58	17	61					
Served orders:	20(58)	8(58)	21(17)	15(61)				
Remaining orders:	4(2)	12(28)	1(5)	17(9)				
Total costs:	C(4)							

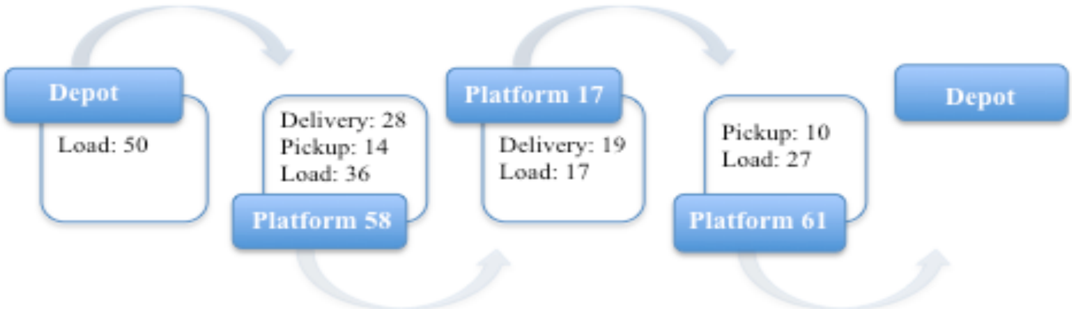

Figure 5-7: *Model solution period t +1*

The remaining orders from time t are added to the list of orders for t+1. In this period, platforms 58, 17 and 61 are visited, so orders 20(58), 8(58), 21(17) and 15(61) are served. Platforms 2, 28, 5 and 9 are not visited, so orders 4(2), 12(28), 1(5) and 17(9) remain in the end of the period, and are moved to period t+2. As shown in Figure 5-2, all other orders can be served on this departure without violating the capacity constraint. Hence, no additional costs arise due to lateness of orders in this period, making the total costs equal to those in period t.

Period t+2:

Remaining orders:	4(2)	12(28)	1(5)	17(9)			
New orders:	16(3)	14(8)	10(1)				
Orders:	4(2)	12(28)	1(5)	17(9)	16(3)	14(8)	10(1)

This example shows the basic features of the model for a short horizon. In theory, all the periods in a year are treated in this way for the simplest version of the model. The loop moves to the next period as long as the stop criterion is not reached.

Chapter 6

Alternative formulation

Chapter 5 displayed four different model formulations differing in the routing policy used. What all models have in common however, is the supply order problem. Considering the routing aspect, the SOP-DR-2 formulation is the less restricted solution-wise. At level 3.2 routes are made dynamically and each platform is allowed two visits during the same voyage. This formulation shows potential for further use, where the routing policy applied is completely altered just by forcing some additional restrictions and constraints. From such adjustments the routing policies at levels 1, 2 and 3.1 result, in addition to the already level 3.2 practiced. This is addressed in the following, where the SOP-DR-2 formulation serves as a basis for when a common model formulation, applicable for all the routing levels studied is created.

Section 6.1 explains the different solution shapes that can be obtained from model level 3.2. This is included to give a better understanding to why the corresponding SOP-DR-2 formulation is used in this setting. Section 6.2 proposes the much-needed adjustments to make the formulation applicable at routing levels 3.1, 2 and 1 respectively.

6.1 Route shapes

The dynamic generation of routes allows the vessel to visit a given platforms two times during a voyage, where the possibility of performing pickup and delivery separately is set as an alternative. The SOP-DR-2, which uses routes at level 3.2 represents such a formulation, as it allows the creation of feasible route solutions in which any platform can be visited once or twice during a given departure.

Gribkovskaia et al. (2007) distinguish between four different solution shapes for the general single vehicle pickup and deliver problem (SVPDP): general (G), lasso (L), Hamiltonian (H), and double-path (D). The general solution is unrestricted in the sense that any customer can be visited once for a combined pickup and delivery service, or twice if these two operations are performed separately. Hence, general solutions include all possible feasible shapes. The SOP-DR-2 formulation could potentially achieve all solution shapes, depending on the SOP applied. This includes lasso solutions, as well as Hamiltonian and double-path. A *lasso* solution consists of a spoke rooted at the depot and of a loop incident to the end of the spoke, leading to formation in the shape of a lasso. An example of a lasso solution is illustrated in Figure 6-1.

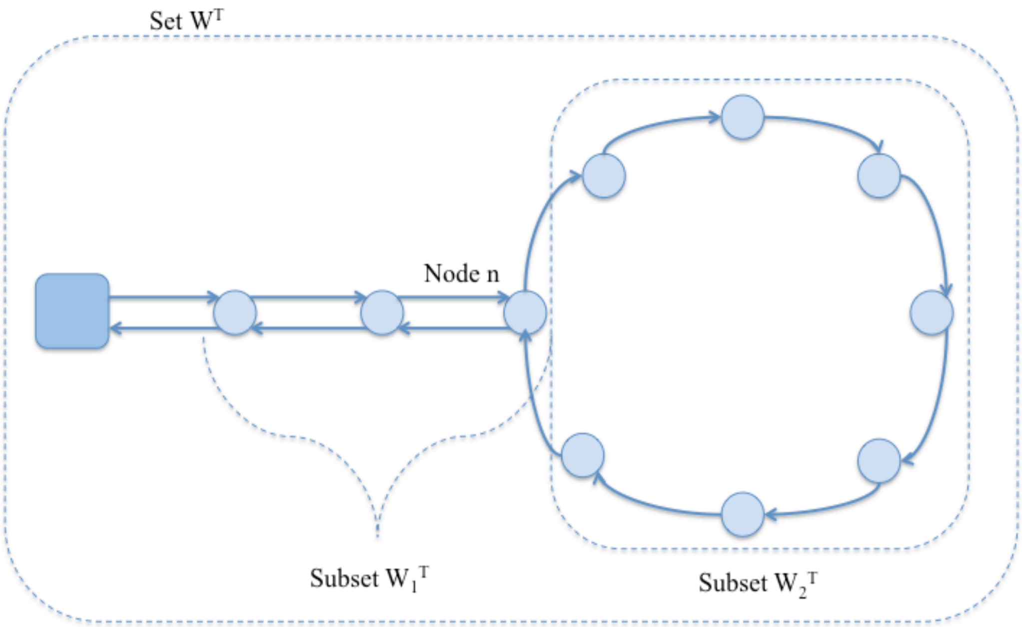

Figure 6-1: A lasso solution

In a lasso solution however, the shape is restricted. Explaining the illustration in Figure 6-1, supplementary notations are needed in addition to the ones formulated in Section 5.4. The subset of W, W^T represent the complete node set of the route, where $W^T = \{0, \ldots, \overline{W^T} + 1\}$ and $v_i = 1$ for all $i \in W^T$. The PSV first performs deliveries along a path rooted at the depot to a subset ${W_1}^T$ of nodes, until it reaches a certain node $i = n$. All nodes of $(W^T \backslash \{0\}) \backslash {W_1}^T$, corresponding to subset ${W_2}^T$, are then visited once for a combined service along a loop until the vehicle reaches node n again and performs pickups to the customers of ${W_1}^T$ by following a path leading to the depot. Node 0 is the depot while the remaining nodes are offshore facilities included in the yielding node.

If ${W_1}^T = \emptyset$ (empty set), the lasso reduces to a Hamiltonian solution, which yields a TSPDP. If ${W_1}^T = W\backslash\{0\}$, the lasso reduces to a double-path solution. The double-path solution can also be obtained by solving a traveling salesman problem with backhauls (TSPB), where all delivery customers must be visited before pickup customers. This can be achieved by duplicating the customer set into the union of a set of linehaul customers with delivery demands Q_{o^d} and zero pickup demands, and a set of backhaul customers with zero delivery demands and pickup demands Q_{o^p}. All four solution shapes are illustrated in Figure 6-2.

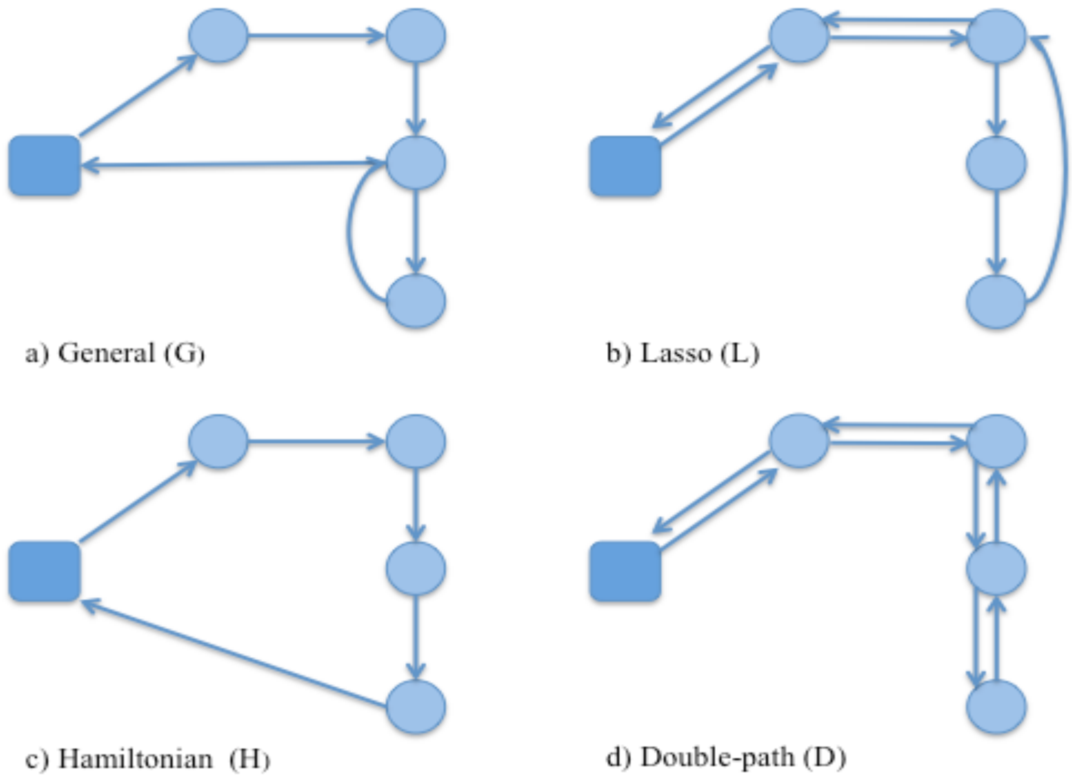

Figure 6-2: *Four solution shapes for the general SVPDP with combined demands*

As seen in Figure 6-1, the PSV first performs deliveries to a subset ${W_1}^T$ of platforms in a lasso solution. Then it visits all the remaining platforms where it performs a combined pickup and delivery, and finally performs pickups only at the vertices of ${W_1}^T$. There exist two types of extreme cases for such a lasso solution: *Hamiltonian* and *double-path*, which were first described by Halskau and Løkketangen (1998) and Gribskovkaia et al. (2001) for a vehicle routing problem with pickups and deliveries.

Hamiltonian solution is generated when all platforms are visited only once, where all pickups and deliveries are done simultaneously or only deliveries or pickups for a given platform are conducted.

Such a solution can be forced by adding the following constraint to the model formulation in Section 5.4:

$$v_i + v_{i+\bar{P}} - x_{i,i+\bar{P}} \leq 1 \qquad i \in W^D \tag{6.1}$$

Constraints (6.1) state that if both nodes i and $i + \bar{P}$ corresponding to the same platform are served, one has to travel directly between the two nodes, corresponding to simultaneous operations. *Double-path* solution however, is generated when all platforms will be visited by means of two Hamiltonian paths, where one is from the depot to some node i, and the second is from node $i + \bar{P}$ to the depot, where nodes i and $i + \bar{P}$ corresponds to the same platform p. In such a solution only platform p has a simultaneous pickup and delivery, while the rest of the platforms are visited twice, separating the service of pickup and delivery. This can be obtained by adding the following constraints to the formulation in Section 5.4:

$$\sum_{i \in W^D} x_{i,i+\bar{P}} = 1 \tag{6.2}$$

$$\sum_{j \in W} x_{ij} = \sum_{j \in W} x_{j,i+\bar{P}} \qquad i \in W^D \tag{6.3}$$

Constraints (6.2) allows only one simultaneous service I a voyage, while constraints (6.3) forces nodes i and $i + \bar{P}$ to be visited the same amount of times.

As earlier mentioned, if the solution has no predetermined shape and no constraint restricting the number of platforms that can be visited twice, it is referred to as a *general* solution. Figure 6-3 illustrates the feasibility of each of solution, where G, L, H and D denote the sets of feasible general, lasso, Hamiltonian and double-path solutions respectively.

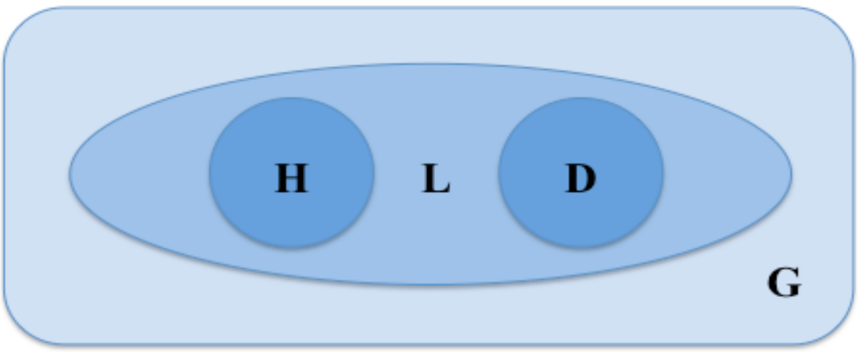

Figure 6-3: *Feasible solutions*

The different solution shapes can be compared as well. By letting z^*_X denote the optimal solution value for the shape X, where X can be D, H, L or G, the relationships between the solutions are the following:

$$z^*_G \leq z^*_L \leq z^*_D \quad \text{and} \quad z^*_G \leq z^*_L \leq z^*_H$$

As lasso solutions are restricted more optimal results could be gained by situations where the lasso shape is non-existing. In the present study this largely depends on order properties and vessel capacity. With small pickups compared to deliveries the incentive to follow a lasso-shape is reduced, as the average pickup would be served simultaneously with delivery. But if despite this, situations where pickup demand is larger in size compared to delivery present themselves in addition to vessel capacity restricting simultaneous services, a second visit to the same platform may be necessary. A lasso shape is however not necessarily induced. As travel distances are taken into account as well, the solution shape produced depends on the platform placements. The example in Figure 6-4 depicts a situation where a non-lasso solution is optimal. The pickup and delivery demands are indicated by (Q_{o^p}, Q_{o^d}) and costs are applied at the arcs.

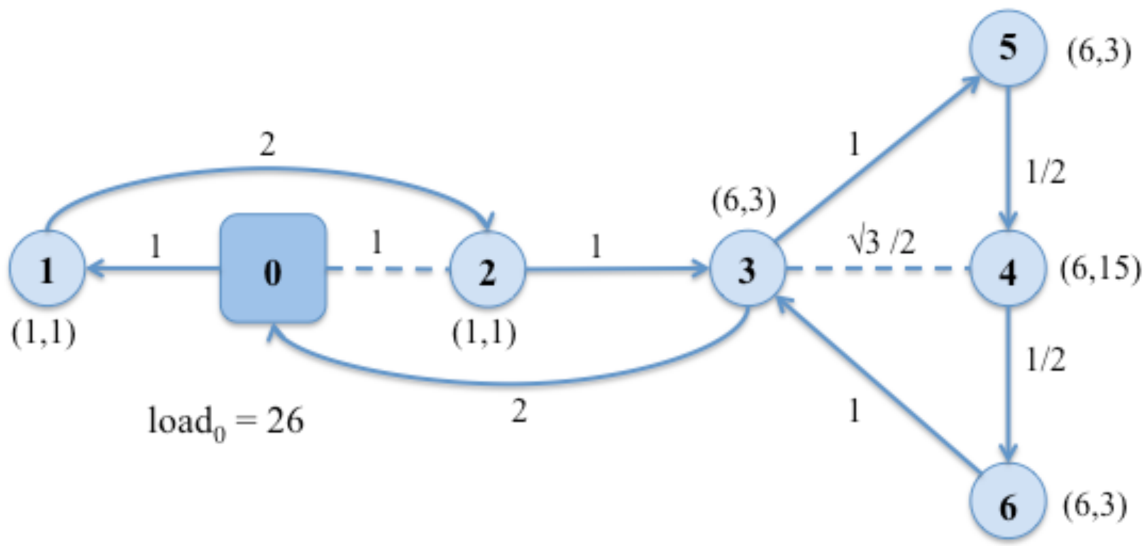

Figure 6-4: *An instance for which the non-lasso solution is optimal (Gribkovskaia et al., 2007)*

The best lasso solution in Figure 6-4, which is also Hamiltonian is $(0,1,2,4,5,6,3,0)$ and has a cost of $8.5 + \sqrt{3}/2 = 9.36$. However, with additional restrictions applied the best non-Hamiltonian lasso solution is $(0,1,2,3,5,4,6,3,2,10)$ with a cost of 11, while the best double-path solution is $(0,1,2,3,5,4,6,4,5,3,2,1,0)$ and has a cost of 12. None of these solutions are optimal though. The optimal solution in this example has a non-lasso shape and a cost of 9, which is $(0,1,2,3,5,4,6,3,0)$.

6.2 A collective model formulation

The latter subchapter illustrated different solution shapes that could be present with the use of model level 3.2, which is unrestricted in the sense that all platforms can be visited once or twice. Most of the SOP-DR-2 formulation used for model level 3.2 could however be applied to model levels 1, 2 and 3.1 as well, as long as adjustments are made. This subchapter starts by explaining how the model 3.2 formulation is adjusted to model 3.1, before further restrictions considering the input data follows applied to levels 1 and 2 as well.

Model levels 3.1 and 3.2 are sublevels of a common level 3, where routes are made completely dynamic based on demand requests for each departure. In level 3.1 on the other hand, the solution shape is restricted. The only solution shape possible is a Hamiltonian, as all platforms visited are served once for pickup or delivery only, or for simultaneous operations. Following this, constraints (6.1) should be added to SOP-DR-2 formulation, restricting the problem from serving the same platforms twice. With this addition, a level 3.1 routing policy has replaced the previous. Comparing this to the SOP-DR-1 formulation as presented in Section 5.4 of Chapter 5, two nodes are now coupled to each platform, differing in order service being pickup and deliveries. However, constraints (6.1) restrict the problem from serving additional nodes in between the services of two nodes coupled to the same platform. This is forced by saying that if both nodes coupled to the same platform are served, i and $i + \bar{P}$ respectively, the vessel has to travel directly between node i and $i + \bar{P}$, where $x_{i,i+\bar{P}} = 1$.

The fixed routes currently in use only allow one visit to platforms in the duration of a departure. So if both pickup and deliveries are served to the same platform the services are performed simultaneously. This is till applied when flexible routes are introduced, where the option to exclude platforms from a yielding route is presented. With the constraints (6.1) in use, the alternative SOP-DR-2 formulation is now applicable for routing policies where platforms are only allowed one visit. As mentioned, this policy applies to levels 1 and 2 as well, where in addition the fixed routes currently in use restrict the problems further. Hence, the input data must be altered when implementing these routing policies. At level 2 the predetermined routes determine the arcs existing for each departure. Naturally, the only existing arcs in this situation should be the ones coupled to platforms present. However, further restrictions are present as well. As the SOP-FR formulation in Section 5.2 of Chapter 5 explained, nodes coupled to each platform are numbered by the sequence in which the corresponding platform is visited in the predetermined routes. Even if flexibility is added the vessel has to travel toward increasing node numbers. Relating this to arcs allowed, only arcs between increasing node numbers can be travelled. The remaining arcs should be excluded from the input.

Taking level 1 into consideration however, further input restrictions should be applied. At this model level routes are completely fixed. This implies that the only arcs present are the ones following the routes in their correct sequence. In addition to this, as there no longer exists any option to exclude platforms from a yielding route, all arcs present should be forced to 1. With these alteration included, a routing problem is no longer solved, which corresponds well with the simple SOP problem formulated in Section 5.2.

Figure 6-3 shows the feasible solutions based on restrictions concerning solution shape. The less restrictions present, the better the solution. With this in mind, on would except the level 3.2 output to be the most optimal, as it is formulated with the potential to achieve all solution shapes. Figure 6-5 illustrates a prophecy of the solutions produced when implementing all levels of routing policies. As the routing policies at levels 1 and 2 faces additional restrictions, the solutions formed are expected to be even less optimal compared to level 3.

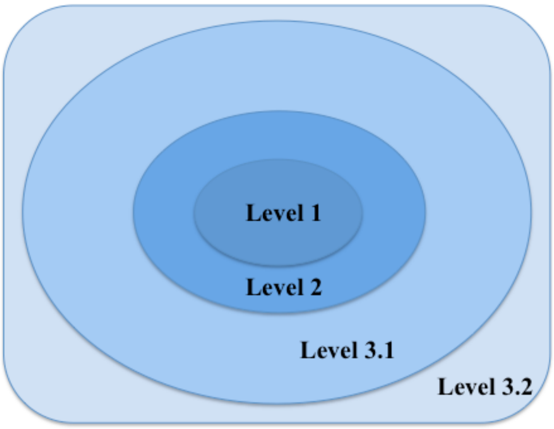

Figure 6-5: *Feasible solutions using different routing policies*

However, this mostly applies for a single departure evaluated in isolation. When the horizon rolls, decisions made in on departure affects the following. It is not given that the most optimal outcome concerning one-iteration alone applies for all iterations in total. Bearing this in mind, it will be interesting to evaluate the output produced when all model levels are implemented. The implementation is explained in the next chapter, before the computational study is presented.

Chapter 7

Implementation

All models were formulated for a single departure in Chapter 5, and an expansion was described and illustrated when considering the supply order problem. In the following part of the paper, the model implementation and inputs used are explained. In Section 7.1, the software is presented briefly, before pre-processing methods concerning the implementation of model constraints are explained in Section 7.2. The models are simple for a single departure in isolation. However the rolling horizon principle, where the problem is solved for one departure at a time with new inputs and outputs each departure, complicates the implementations. Section 7.3 aims at explaining the implementation in the software used, where all models are solved for the number of departures corresponding to a year in total.

7.1 Software

The models are implemented in the commercial optimisation software Xpress. The version used is Xpress-IVE 1.24.00 64-bit with modelling language Xpress Mosel Version 7.7.0. Input to Mosel is a .mos file that contains the model to be solved. This .mos file is compiled, which result in a binary model (BIM) that is saved as a .bim file. The model is run when Mosel reads the BIM file and executes it. As Mosel does not integrate a solver by default, connections through external solvers through modules are used. Mosel is connected to the Xpress-Optimizer through the module *mmxprs*, which through the procedure *minimize* optimizes the problem at hand.

The program is run a total number of 64 times, with some changes in the models used and data input in the different executions. Xpress reads data from a text file where static parameters are given. All models, input files and program runs can be found in Appendix G.

7.2 Pre-processing in software

The formulations were to a great extent modelled in the same way as they are formulated in Chapter 5. However, constraints (5.3), (5.12), (5.24) and (5.37) were defined when declaring the models' variables instead of being modelled as constraints.

In addition, an alternative formulation considering the numerous subtour elimination constraints (5.26) and (5.40) in sublevels 3.1 and 3.2 respectively, were implemented. These constraints, as formulated in Chapter 5 complicated the problems up to the point where no solutions can be obtained. Instead, subtour elimination was implemented by creating some additional variables and constraints.

Variables

f_{ij}	$(i,j) \in A^1$	Subtour elimination variables for level 3.1, adding 1 for each node visited
f_{ij}	$(i,j) \in A^2$	Subtour elimination variables for level 3.2, adding 1 for each node visited

Constraints

$$f_{ij} \leq M_1 \cdot x_{ij} \qquad (i,j) \in A^1 \tag{7.1}$$

$$\sum_{j \in V} f_{ij} = \sum_{j \in V} f_{ji} + v_i \qquad i \in V^F \tag{7.2}$$

$$f_{ij} \leq M_2 \cdot x_{ij} \qquad (i,j) \in A^2 \tag{7.3}$$

$$\sum_{j \in W} f_{ij} = \sum_{j \in W} f_{ji} + v_i \qquad i \in W^F \tag{7.4}$$

Flow variables are used in the implementation, where they are coupled to arcs and increasing with each new node visited in a departure. As an example, if the vessel travels directly from the depot to node 37, before node 2 is visited, the corresponding flow variables $f_{0,37}$ and $f_{37,2}$ are given the numbers 1 and 2 correspondingly. Constraints (7.1) and (7.3) make sure that the flow variables are set to zero if the corresponding arc is not travelled. The parameters M_1 and M_2 sets the maximum number of node visits allowed during a voyage. These numbers were however set large, as the actual voyage duration should restrict the problems. This is further explained in the next section. Constraints (7.2) and (7.4) add 1 to the flow variables for each new node visited. If node i is visited, where $v_i = 1$, the sum of all flow variables travelling from node i is equal to the flow variable travelling to node i, plus 1. Constraints (7.1) and (7.3) are applied to the level 3.1 model formulation, while constraints (7.2) and (7.4) are used in level 3.2. The complete model formulations using these subtour-eliminating constraints are given in Appendices E and F, for levels 3.1 and 3.2 respectively.

7.3 Model implementation

In the implementation of the model some technical procedures that connect the different inputs to the model are explained. Next, the dynamic aspects are described, with emphasis on the order generation and the way the implementation moves between the departures. A loop is entered and updated for each new departure as the horizon rolls. In the end of the implementation a simplification of this basic model loop is illustrated, showing the connection between inputs and the dynamic characteristics.

7.3.1 Inputs and declarations

A route is either represented by node numbers corresponding to platforms, or directly by platform numbers. This all depends on the model level in use, as further explained in Chapter 5. An additional sequence index is introduced in model level 1 to allow counting over the platforms in the correct order. With model level 1 being the case, the input to the route is a sequence number and it returns the number of the platform visited at this position in the route. For instance, the second platform visited on a specific journey is given by $Route(2)$, which returns the corresponding platform number. Route with corresponding sequence numbers are still given as input when model level 2 is applied. In this case, the input routes are used as restrictions concerning which arcs the vessels can travel in different departures. In level 3 however, the fixed and predetermined routes are no longer yielding, as routes are made completely dynamic for each departure considering the arcs and corresponding distance matrices.

A similar method as for the coupling between routes and sequence numbers connects the orders with platforms and demands, where orders are represented by a number going from 1 to the total number of orders generated. All these orders are linked to the number of the platform requesting them. The notation $3(2)$ means that order number 3 belongs to platform 2. In addition, a list of the same size as the order list consists of numbers linking the order number to a demand quantity. Table 7-1 shows the interconnection between platforms, orders and demands. Demand Q_3 is for instance the area taken up by order number 3, and this order belongs to platform 2. Orders are divided into two subsets, one for deliveries and one for pickups, all with positive demands.

Platform	Deliveries	Pickups
1	Order $1(1)$: Q_1	Order $2(1)$: Q_2
2	Order $3(2)$: Q_3	Order $4(2)$: Q_4
3	Order $5(3)$: Q_5	Order $6(3)$: Q_6

Table 7-1: *The interconnection between platforms orders and demands*

When the model is implemented in Xpress, all parameters, variables and constraints are declared and initialised. The binary decision variables are created within the loop for each new departure, to simplify the solution process. The load variables are created before the loop is entered and further updated inside the model loop.

7.3.2 Dynamic parameters and order generation

The order generation is a special feature of the model. All orders are generated prior to the model loop, meaning prior to the first departure entered. Platforms have on average two delivery and two pickup orders per week, since most platforms are visited twice during a week. The demands are generated randomly from a uniform distribution with bounds given in the input file, with sizes and numbers according to the platform set they belong to and their order type being delivery or pickup. All the orders and corresponding demand quantities are saved in matrices inside the model.

When the program moves into the loop, it is run for all the departures in a year. Since departures are at different times of the day, they are treated as separate periods, such that new orders are received per departure and not per day. With 13 departures a week and including leap years, there are 678 departures and corresponding periods in a year. The model moves from one departure to the next automatically, recording the output from each.

For each new departure, a dynamic array takes in an arbitrary subset of the orders, representing the orders that the logistics central onshore receive at this point in time. This list is called New. For each departure, these orders are moved into a different list called $Active$, combining the new orders with the orders that are yet to be served from previous periods. New is emptied at the end of each period. The orders in $Active$ are the orders that are relevant for the current problem. Some of these are not served, as this depends on the corresponding platforms visited, and will be saved in the list until the next departure. Orders that are served on the departure are taken out of $Active$ and recorded in a different array along with the served orders from all periods. The interplay between these dynamic parameters ensures that orders will be transferred to the next period as long as their corresponding decision variable has the value zero.

In model level 1, where the voyage is set for each departure, a supporting constraint forces the decision variables for orders to zero when the platform is not visited in the beginning of each departure. This reduces the problem of the given departure. Load constraints are similarly only applicable to orders belonging to platforms found in the associated route. This could potentially be implemented in model level 2 as well. But as the actual routing aspect is taken into consideration in model level 2 as in model level 3, a similar implementation for these model levels are formulated. Actually, model level 2 is formulated based on the level 3 formulation, as explained in Chapter 6.. This is implemented by setting some additional restrictions considering the actual arcs than can be travelled, considering the fixed and predetermined routes as inputs.

In model level 3, the solution time becomes an issue due to the numerous of variables and constraints considered. Some simplification is however considered in the implementation to reduce the problem for each departure. For example, as there exists no reason to serve platforms and the belonging node(s) if no orders are requested, decision variables considering which platforms to serve are only created if corresponding order requests are present. Following this, arc variables are only created between existing node variables for each departure.

7.3.3 Costs and model outputs

The order costs are minimised for each departure. This is sensible since decision makers do not know future requests until the departure in which they are placed are taken into the problem. So for each time the loop runs over a new departure, the orders are distributed to minimise the costs related to them if they are not served. Travelling costs comes in addition in model levels 2 and 3. Before entering the loop, the costs for all orders are initialised and given a value to make sure the objective function solves the problem properly. The order cost increases every time the loop moves from one departure to the next. An order served on the first departure possible does not carry any costs. Travelling costs however, are initialised to zero at the beginning of each model loop, and further calculated based on voyage that is either fixed or presents it self as the most valuable considering both the minimisation of order delays and distances between facilities. In the end, after all 365 days (678 departures) have been accounted for, the total cost is found by adding together the costs for the complete set of orders, in addition to the the variable sailing cost multiplied by all voyage distances conducted.

In addition to the total cost, the model is implemented to save other kinds of information that are given as outputs when the program is finished. Orders that are not served on their first possible departure are saved and counted, including the number of feasible departures they had to wait before being served. The demand quantity for those orders is also added up. These measures give an idea of the situation in physical terms, with an understandable description of the effect of constrained capacity.

7.3.4 Model illustration

Figure 7-1 is an illustration of the basic model loop, showing how demands are generated and delay costs are optimised for each period. The departure number is updated each time the loop is entered, which gives a total number of loops equal to the number of departures in the planning horizon. The stop criterion for the loop is when the final period T is reached.

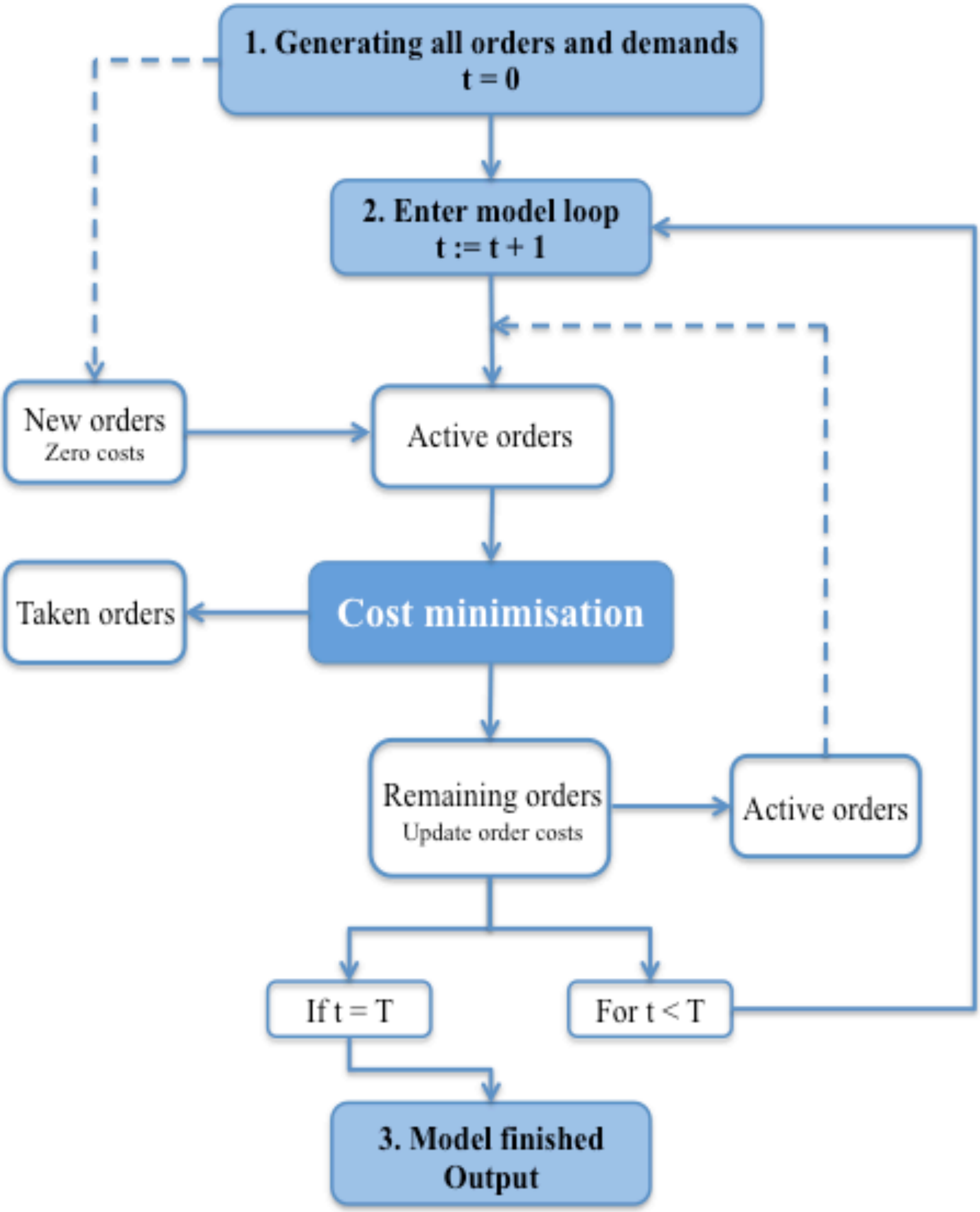

Figure 7-1: *The basic model loop*

Chapter 8

Case study

The previous chapter explained the implementation of the model used for the analyses. In this chapter, additional preparations considering the computational study in Chapter 9 is presented. Section 8.1 describes the input data applied, before the different cases and situations used are described and justified in Section 8.2. In addition, important model output is stated, with the aim to make the analysis in Chapter 9 more readable in Section 8.3.

8.1 Input data

The mathematical models formulated in Chapter 5 are in need of realistic data input to be valuable. The input data are a combination of statistics received from Petrobras and assumptions and simplifications. The author's intention is to mimic the actual situation as closely as possible when parameters are concerned, in order to draw conclusions that may be valuable to the decision makers at Petrobras. The most important aim has been to develop credible and useful models so future research may be based on the findings while taking more data into account. Therefore, the rest of the paper is based on the information available at the time of implementation. This section presents the most important input parameters used in later computational studies.

8.1.1 Vessels

Petrobras currently operates with two types of platform supply vessels, the PSV 3000 and the PSV 4500, when orders are supplied to offshore facilities using scheduled departures. The common operating speed is 10 knots (18.5 km/h). The only differences between the two vessels are the deck capacity and costs. The deck spaces are 620 square meters (Friedberg and Uglane, 2013) and 840 square meters (Guido Perla & Associates, Inc., 2013) for the PSV 3000 and the PSV 4500, respectively. Each vessel is normally utilized for two voyages during a week.

As the vessel fleet operated by Petrobras are fixed and predetermined, which type of PSV utilised in a given departure depends on the availability at port. This means that when planning for a departure, decision makers are not free to choose which PSV to use depending on the amount of orders requested. Taking this into account, one vessel type should be chosen for the total planning duration. PSV 3000 is currently much more available compared to PSV 4500. Contemplating this, in addition to the fact that a PSV 3000 and costs significantly less considering the difference in capacity, it is assumed that the use of a PSV 3000 with corresponding capacity of 620 square meters in all departures is a reasonable choice.

8.1.2 Order specifics

Data from Petrobras give the total load and backload transported for each month. The load is around 21 000 and backload 7 000, so pickup demand quantities are on average one third of the deliveries, which is stated in the input file to the model. From these data, the average demands are also estimated. The monthly load is uniformly distributed between approximately 156 departures depending on the number of days in the month. This is used to find upper and lower bounds for the demand sizes considering the average number of platforms visited on a departure. The delivery size range is set between 35 and 55, and 10 and 90 for production and drilling orders respectively. This puts the average delivery order on 45 square meters in total. Demands are drawn from this distribution randomly when generated. Each production platform request two delivery orders one average a week, as approximately all platforms are served two times in a week, while drilling platforms request four orders on average a week. Altogether, the size and number of pickup orders comprise to one third of the delivery orders in demand in total. Each order is coupled to both a platform and departure.

Imitating the present situation, different priorities can be put on orders. With such a priority system being the case, each order is either labelled normal or emergency. The term emergency is used when the platforms require the cargo to be delivered earlier than 10 days after the transfer requests (RT) is recorded in SAP. Hence, a strict delay limit is put on emergencies. The delay limit is set to 8 departures, which is based on a simple calculation given in Appendix B, taking onshore order handling and time consume into consideration. If the delay limit is reached for emergency orders, and unplanned express is conducted. As of today 50 % of orders are labelled emergencies. Based on estimates form the cargo consolidation department, the actual portion of emergency requests should be 10 %. As 50 % and 10 % emergency requests are mentioned, they are both tested to see their implications on different parameters settled in the next chapter.

In addition, different maximum delay limit may be tested on normal orders as well. Delay limits in this case, like the one considering emergencies, are implemented as so called express policies. This means that if an order is not served within its set delay limit, an express vessel in conducted on the same departure in which the delay limit is reached, serving the order as quickly as possible. Petrobras do not have any express policies considering normal orders that the author know about. However, as express vessels are currently being conducted in a frequent matter, some underlying rules and policies not stated may be in use. With this in mind, testing for different delay limits on normal orders as well should be applied. Different limits tested are 20 and 15 days for normal orders. Using the same calculation strategy as the one presented for emergencies in Appendix B puts the delay limits in departures to 27 and 18 for 20 and 15 days, respectively.

Additional important numbers that need to be settled considering orders are the costs for overdue delivery. As these costs comprise most of the objective function in all model levels, setting the right amounts are of great significance. The delay costs for overdue delivery of an order are shown in Table 8-1 under “Costs”.

8.1.3 Facilities

There are currently 52 offshore facilities in the Campos Basin that are visited on a regular basis by supply vessels. Petrobras have named the platforms in an internal system according to the facility type. In this manuscript, a number between 1 and 52 represents each platform. The complete list of platforms can be found in Appendix A, including original names and given numbers. The depot, representing the port in Macaé is given the number 0.

To imitate the variations among the facilities due to sizes and operations, such as different life cycle stages of the related oil fields or technical requirements, the set is divided into two subsets. A chosen set contains platforms that are given larger and more fluctuating demands than the platforms in the other set, as they represent drilling platform compared to production platforms, and hence require more order supply. The ratio between the large and small sizes is set to 1.5 on average. Some information considering the different platforms being drilling or production was obtained (Click Macaé, 2014). As not all platforms were mentioned in the in the obtained information, some assumptions had to be made here, where the given platform names and placements helped. Altogether 12 platforms are categorised as drilling, while the remaining 40 are production platforms. An overview of the different platform sets can be seen in Appendix A.

The distance matrices used as input in model levels 2 and 3 when considering the distances travelled, are calculated based on facility coordinates. The hardest task considering platform information was their actual whereabouts. As the present platform coordinates are valued as confidential information and can correspondingly not be obtained from Petrobras, some creative methods were applied. This procedure is described in more detail in Appendix B, followed by the coordinates obtained and the distance matrix calculations. Figure 8-1 shows the facility placements based on their estimated coordinates.

The complete matrices, using both a single-node- and two-node-formulation depending on the level, can be found in an excel file in Appendix G. As most of the facilities are platforms, it should be safe to assume that their positions are fixed during the planning horizon presented in this thesis. The port in Macaé is located approximately 34 kilometres from it nearest platform, while 224 kilometres is the distance between the port and the platform farthest away. So large distances are considered.

Figure 8-1: *Facility placements*

8.1.4 Routes and departures

There are 13 departures in total during a week, with 12 hours gap in between except for the single Sunday departure. Petrobras' current PSV schedule is shown in Table 2-1, with numbers representing the platforms visited. The original timetable for Petrobras is given in Appendix A, where the only difference is the use of the original platforms names. One can see that each route includes six to nine platforms. All routes begin and end in the port of Macaé. In addition, all platforms are visited a total of two times each week except for six platforms that are visited once a week. Hence, it is safe to assume that all platforms should be treated equally, and only be based on the subset of platforms that they belong to. The route schedule is used as input to the model.

When routes are made dynamic in model level 3, voyage duration must be settled. It is already given that vessel could be used for two voyages in the duration of a week. With this information it is tempting to assume that all voyages are of approximately equal duration, considering half a week in total. But regarding an assumption that all departures can be treated equally, some additional information was settled. This is especially important, as all vessels need to be back to port in time for the next departure. Otherwise delays may follow. The duration limit used is based on the current voyage duration using the fixed and scheduled routes. In Appendix B the complete procedure when calculating the maximum voyage duration is given. With a common operation speed of 18.5 km/h, assuming a 4-hour offshore service for each platform visited, and setting the maximum voyage limit to 72 hours, the actual sailing limit can be obtained. This is implemented by creating additional constraints in the models presented in level 3. In doing so, some extra parameters must be settled in addition to the ones presented in Chapter 5.

Parameters

S	Operating speed, which is common for both PSVs in use
T^S	Service duration on a single offshore facility served
T^L	Total voyage duration limit, excluding port operations

Constraints

$$\frac{1}{S}\sum_{(i,j)\in A^1} D_{ij}x_{ij} + T^S\sum_{i\in N^F} v_i \leq T^L \tag{8.1}$$

$$\frac{1}{S}\sum_{(i,j)\in A^2} \bar{D}_{ij}x_{ij} + T^S\Big(\sum_{i\in N^F} v_i - \sum_{\substack{(i,j)\in A^2| \\ j=i+\bar{P}}} x_{ij}\Big) \leq T^L \tag{8.2}$$

Constraint (8.1) is added to the model level 3.1 formulation, where platforms served are only allowed one visit in the duration of a departure. The constraint is formulated in hours. The first term gives the sailing duration, where the total distances travelled in kilometres must be divided by the common operation speed given in kilometres per hour. The second terms gives the total service duration on offshore facilities. There is a trade-off between the distances travelled and the total number of offshore facilities that can be served during a voyage. Constraint (8.2) is added to the model level 3.2 formulation, and is expressed similarly as constraint (8.1). A third term is however added considering the situations where a vessel performs simultaneous pickups and deliveries. As two nodes are coupled to each offshore facility, problems arise in situation where pickups and deliveries are performed in the same visit. In these situations the service duration should only apply for one node coupled to the yielding platform, as only one platform visit is conducted. As two services are already added to the respective offshore facility in the first term, one service duration must be subtracted in cases where $j = i + n$, meaning that the arc between two nodes corresponding to the same platform is visited. Complete mathematical model formulations including voyage duration constraints are given in Appendix E and Appendix F.

8.1.5 Costs

Besides the described input data above the cost coefficients are of importance, as the objective functions in all the models formulated in Chapter 5 minimises total costs. These costs can be divided into two groups: direct and indirect costs. Directs costs are the ones related to the distances travelled, which is further split into variable and fixed sailing costs. In addition, when express departures are implemented in the problem, express costs are considered as well. Express costs goes under the category direct, as they are to some extent given and fixed. Indirect costs however, are the ones coupled to order delay. These are estimated purely from the author's subjective opinions and do not reflect any actual transport or inventory costs. The direct and indirect costs of concern are explained in more detail in the following.

Direct costs

Concerning the model of a single departure seen in isolation, the only directs cost of importance is the variable, as it is assumed that the planned use of PSVs is still conducted. Petrobras currently operates with PSV 3000 and PSV 4500 when serving platforms with supply, and with PSV 1500 and PSV 3000 when an express is conducted. The direct costs associated with these types of vessels are summarised in Table 8-1.

Vessel type	Variable cost [per km]	Fixed cost [per departure]
PSV 3000	$ 420	$ 122 500
PSV 4500	$ 630	$ 157 500
Express PSV 1500	-	$ 350 000
Express PSV 3000	-	$ 490 000

Table 8-1: *Direct costs for the PSV 3000 and the PSV 4500*

The fixed costs are based on daily rates for PSV 3000 and PSV 4500 of $ 35 000 and $ 45 000 respectively. As all schedules routes are given a return limit corresponding to approximately 3.5 days, the lease rates of PSV 3000 and PSV 4500 are multiplied by a factor of 3.5 for a departure. The variable costs, on the other hand, mainly consist of the fuel consumption, which is supplied by Petrobras. In addition, the variable costs include operating costs that are in most contracts paid by a third party operator.

It is known that the costs of leasing an express vessel corresponds to approximately the doubled compared to a schedules PSV based on daily rates. In addition, the leasing estimate in this case includes both fuel and operating costs, where no additional attention is given to the actual voyage duration and distances travelled when an express is conducted. Unlike scheduled PSVs, express vessels are leased for a week at the time. However, as they are leased on a short notice assuming no additional time to plan for additional use than for the departure they are leased, the complete week leasing costs are applied for a single express departure in this case study. Savings could of course occur if the express vessels were better utilised, but as reason for using express is to serve orders, especially emergencies in a quick manner, no additional attention considering planning her is taken into account. The total express costs are based on daily rates for PSV 1500 and PSV 3000 of $ 25 000 and $ 35 000 respectively. This sets the daily leasing rates to $ 50 000 and $ 70 000 for express vessels. As mentioned, each express is leased for a week, where the lease rates are multiplied by a factor of 7. This puts the total express cost for a departure to four times the fixed cost of scheduled vessels. However, as variable costs come in addition for schedules vessels, which comprise large sums as severe distances are travelled, the total difference is not four times in total. Nevertheless, an express departure is an extremely costly operation, which comes in addition to the already scheduled PSVs.

Indirect costs

The indirect costs in the models formulated consist of costs that represent the inconvenience of delay. These costs are estimated based on the author's subjective opinion, although existing costs are taken into consideration. The purpose of these costs is rather to set a standard making it easier to compare different results from the analysis. The parameter is fully adjustable. The order costs depend on the specific order size, where a chosen fraction is multiplied with the demand quantity for pickups and deliveries. Deliveries are assumed more important and their cost coefficients are accordingly higher.

When numbers are concern, balancing costs coupled to the inconvenience of delay with the travelling costs becomes important in model levels 2 and 3, as both costs are part of the objective function and have contradicting effects. It is assumed that more weight should be put on order lateness, as demand service is an extremely important operation considering the costly platform operations requesting. Delays may result in production disruption, which may potentially trigger expensive consequences. However, they should not be too severe in comparison, as Petrobras in some cases may actually benefit from delaying a small order, especially pickups, in situations where the additional travel distance becomes too costly. To make the vessel expenditure worth its while already at the first departure, it is safe to assume that cost corresponding to order delay at least should correspond to the cost of vessel use. In addition, conducting an express instead should not be optimal. Following this, the possible order delay cost of a departure should be both more than the scheduled vessel cost and less than express. The calculation conducted is given in Appendix B, where proposed costs per demand delayed in square meters for both pickup and delivery are proposed as $ 400 and $ 800 correspondingly. Even so, the indirect order delay cost are mostly set to make the supply order problem as efficient as possible. Following this, larger delay cost will be tested as well.

The process of updating the costs was explained in the Chapter 7, while more details about the specific cost functions are given in the case descriptions in the next section.

8.2 Case descriptions

Different cases are developed to analyse the impact of approaches to the problem solving and to examine the importance of various factors when orders are distributed in each model level. Each case with supplementary subcases are presented and justified in the following paragraphs. The variations are divided into two main cases: case A and case B. Case A mainly considers simple order service policies, using direct and indirect information and parameters, aiming at illustrating the presence in the most accurate way order service-wise. This sets the foundation for case B. Case B explores alternative methods to better the situation as of today. The use of alternative routing policies when planning for a departure is explored, in addition to overbooking, which is a way of coping with the fact that a large proportion of orders are no-shows. Further on, the potentials if other parts of the supply chain could be improved are investigated in case B. This could potentially affect parameters like no-shows and emergency orders, and reductions in these are tested.

There are different situations within each subcase of the main cases that could be used depending on the route level. Level 1 incorporates all case situations, as parameters, applications and policies need to be settled at this stage to imitate the present situation in the most realistic way. In addition, it is considered necessary to evaluate the actual effect of introducing parameters like no-shows and emergencies, to further clarify the situation as of today. Only a selection of the situations presented is proceeded with in the level 2 and level 3 analyses, depending on the findings in level 1. All possible cases and situations are presented below.

8.2.1 Case A: Order service policies

The implementations in case A serves as the base case for all model levels, where different decisions have to be made considering the present order service situation at Petrobras. Such decisions consider elements like the cost functions for order delay, vessel capacity, no-shows, emergency orders and express policies. All of these elements are explored in the following, with emphasize on both given information and some underlying issues currently yielding at Petrobras.

The first task is to find the most optimal cost function that should be coupled to delay of orders. This sets the foundation for order service, as a lot of information concerning this topic currently lacks and should be settled before proceeding with the analyses where proposed solutions are applied. To make the analyses more realistic already fixed and given information from Petrobras are used, which considers the fraction of no-shows, and the amount of emergency orders and their express policies. In addition to this, testing for different express policies when normal orders are concerned is performed as well. Putting all of these elements together, the aim is to end up with the supply order problem as of today, which will be further applied when different alternatives considering the routes in use ns model levels 2 and 3 are proposed.

For case A there are different situations based on variations in the parameters applied. A single situation is given with a complete case name of the form:

$$A.X(\alpha, \theta, \tau)$$

Here, X represents the cost function used. Case A can be varied with other parameters as well. Table 8-1 summarises these variable parameters, which in addition to the cost functions are all described in more detail in the following.

Symbol	Name	Description	Values
α	**No-shows**	The percentage of no-show orders	$\{0, 15, 25\}$
θ	**Emergencies**	The percentage of emergency orders that are prioritised compared to the "normal" ones	$\{0, 10, 50\}$
τ	**Delay limit**	The delay limit for normal orders that are served with express if exceeded	$\{18, 27, \infty\}$

Table 8-2: *Case A variable parameters*

Cost function

From the project thesis by the same author (Gausel and Hagen, 2013) considering a more simple version of the supply order problem presented here, different cost functions were tested for, updating delays with both constant and demand dependent values. In the project thesis it was concluded that the most efficient and close to reality cost functions where the ones dependent on the size of demand. Larger demands are thus given a higher priority than smaller ones. The relation is implemented such that there are also higher costs per unit of delivery demands than of pickup demands, reflecting the understood notion that deliveries are more important and should be prioritised above pickups. This approach may imitate the real world well since the delayed delivery of an essential item can in the worst-case cause disruptions in the offshore production. Delayed pickup however, might just lead to a more difficult operating environment with less space on board the facility. Hence, only cost functions emphasising on orders size and type will be used. Following this, three different cost functions are tested for in subcases $A.X$, where $X = 0, 1$ and 2 for cost function 0, 1 or 2, respectively.

Case A.0 represents a first-come-first-served approach. *First-come-first-served* is a common policy in order distribution, and it is used as a base case for comparisons with optimisation based programs. Here, all orders have a low initial cost when they enter the model, and the unserved orders are updated with a larger term every time the order is not served after arrival. This ensures that orders are prioritised according to the time they have been known. The arrival time of the order request is set to the departure in which the order is requested, independent of the corresponding platforms is visited or not when fixed routes are concerned. The term that the lateness cost is updated with for each unserved departure is proportional to order size and orders being pickups or deliveries. All orders have lower initial costs when entering the model compared to the update cost.

In case A.1, the lateness cost of all orders are no longer initialized with a small constant compared to the update cost. Instead all orders are initialised with the same amount as they are updated with, where order type and size are taken into account already from the first departure. The solution may now change compared to A.0, for example if the program chooses to serve two orders with costs of 5 000 each instead of one order with a cost of 10 000. When the update term due to delays are set high in comparison to the initial cost, as in A.0, this opportunity disappears, and the first orders requested are guaranteed to be served first if possible. However, the models in A.0 and A.1 share most features, and the difference between them is not expected to be of great significance.

The time of delay is already accounted for in case A.1, as delay costs coupled to orders increase for each departure not served. This is taken a step further in case A.2, where more weight is put on the actual time of delay. The cost term is still proportional to order size, but in addition each order cost is multiplied with the time of delay squared. This implies that if an order is delayed for two departures, the cost corresponding to the orders is updated with a term as in case A.1, only multiplied with 2^2. This is tested, as one of the biggest concerns of Petrobras is the delay of a large proportion of orders, where order service becomes more critical for each unserved departure passing. The lateness cost of each order is updated with an additional constant as well, emphasising more weight on actual service rather than the distances. This may be of significance when routes are altered in levels 2 and 3.

The cost functions implemented are presented in Table 8-3. The function is called upon in the end of each departure, noted t, and the cost C_o is carried over to the next, where o represents a specific order. The constants used can be adjusted to appropriate values. The values, as implemented in Xpress, are represented in Table 8-3. The first term is the total cost from all previous departures, equalling the initial cost in the first departure $t = 0$ when the order is recognised. For A.0, this is set to 5, a randomly chosen number that is very small compared to the update cost due to delays, to ensure that the orders are served according to the sequence in which they are placed. Making this number larger than zero is still important, as orders should be given a service incentive already at the first departure if possible. The second term is the updated cost term. All cost functions include weighting factors of 800 and 400 for deliveries and pickups, respectively, where the numbers used are justified in the previous section. The alternatives that present themselves as the most robust are selected for the further analysis in proceeding model levels and cases.

Subcase	Cost function	Departure
A.0	$C_o(0) = 5$	$t = 0$
	$C_o(t) = C_o(t-1) + 800 \cdot Q_{o^d} + 400 \cdot Q_{o^p}$	$t \neq 0$
A.1	$C_o(t) = C_o(t-1) + 800 \cdot Q_{o^d} + 400 \cdot Q_{o^p}$	$t = 0$
	$C_o(t) = C_o(t-1) + 800 \cdot Q_{o^d} + 400 \cdot Q_{o^p}$	$t \neq 0$
A.2	$C_o(t) = C_o(t-1) + 5000 + 800 \cdot Q_{o^d} + 400 \cdot Q_{o^p}$	$t = 0$
	$C_o(t) = C_o(t-1) + 500 + (800 \cdot Q_{o^d} + 400 \cdot Q_{o^p}) \cdot {T_o}^2$	$t \neq 0$

Table 8-3: *Order lateness cost functions*

No-shows

As mentioned in the problem description, a major challenge for Petrobras is related to onshore logistics. When supplies are requested from the offshore facilities, these are transported from warehouses and onshore locations to the port where they are loaded onto vessels. A big problem is that approximately 25 % of the orders do not show up at the port in time, and are therefore not delivered to the platforms they belong to until at earliest the next time when the platforms are included in the route. These delayed orders are called for $NoShows$ and they are generated randomly inside the model loop for each departure, after the single-departure problem is solved. $NoShows$ are moved to the list of orders in $Active$ for the next departure and stay until they are delivered, and the cost is updated in the same manner as for other orders that are not delivered in a departure. Consequently, large costs can occur from the delay of arrivals at port.

No-shows are added to the problem to see it implications on order service and delays. The set $NoShows$ is established after the supply order problem is solved for a departure, and it affects the set $Active$ proceeding to the next departure. Since the problem originates onshore, it is only an issue for deliveries and not pickups. This serves a basis in level 1 to evaluate the amount of delays and hence the use of express vessels when imitating the present situation. The use of 25 % no-shows is implemented in case B as well, as this is a known fraction of orders.

Emergency orders

As mentioned in chapter 2, Petrobras currently operates with a priority system when orders are requested. Imitating the present situation, orders can be either emergencies or normal, where emergency orders should be served as quickly as possible. The term emergency is used when the platforms require the cargo to be delivered earlier than 10 days after the transfer request (RT) is recorded in SAP. Consequently, emergency orders that are not served within 8 departures after they are requested are shipped with an express vessel.

To induce emergency service, all emergency orders are initialised and further updated with a large priority cost forcing their service if possible. This cost is set to the symbolic value of $ 420 000, which is correspondingly the average express leasing cost of PSV 1500 and PSV 3000. All emergency orders are generated randomly as a given fraction of orders before the model loop is entered. Orders labelled emergencies are further placed in an additional order set, $Prio$. $Prio$ can contain both delivery and pickup orders, as some special equipment and gear needs to be transported back to port in a quickly manner for updates or re-use on other platforms. All express demand is added in a similar manner, independent of the corresponding order being a pickup or delivery. This is based on the assumption that the only focus considering express vessels is to serve orders as quickly as possible, without having to consider the load on board the vessel at all times. Hence, an express vessel should be able to carry all scheduled demand simultaneously, as pickups might be conducted before deliveries if this is considered most optimal. According to Petrobras, approximately 10 % of orders should be categorised as emergencies. However, it is estimated that approximately 50 % of orders are currently being categorised as emergencies. This implication is studied.

All orders served with express are moved to an additional set $Express$ and removed from the set $Active$, as they are served and no longer should be considered. So, in addition to serving orders with a scheduled PSV, express vessels might be leased during a departure as well. The $Express$ set is initialised to zero for each new departure, and correspondingly only include the specific orders served with express for each departure alone. As earlier mentioned, Petrobras currently operates with PSV 1500 and PSV 3000 as express vessels, where capacity and costs differ. They will further be mentioned as express 1500 and express 3000, respectively. Depending on the amount of express demand in a departure, decisions concerning the type and number of express to utilise are made in each departure. This is modelled in the most cost efficient way, as it is assumed that Petrobras would lease the cheaper of the two it the capacity on-board the express vessel allows it. In occasions where the express demand exceeds the express 1500 capacity, an express 3000 is applied, as this is cheaper compared to the use of two express 1500. The capacities of express 1500 and 3000 are set to 240 and 620 in square meters, respectively.

An approach to deal with the geographic spread of platforms offshore is to carry the largest orders by express, to avoid having to visit several platforms far apart. But as it assumed that when an express is called upon, there is not enough time to optimise the voyage. In addition, express vessels are currently being leased for a week at the time, so no concern is given to travel duration.

Express policy

When normal orders are concerned, Petrobras don´t seem to have any consistent rules considering the service time wise. But as they are currently conducting express vessels in a frequent manner, also serving normal orders, some unmentioned policies seems to exist reflecting the time of delivery for normal orders as well. Following this, testing for different time limits for normal orders are done in case A. This is implemented by setting a maximum delay time on delivery orders. All delivery orders reaching their delay limit should be served with an express vessel to avoid production and drilling disruption on platforms, and are further placed in the $Express$ set. The delay limit is only set for delivery orders and not pickups, as no-shows are only an issue for deliveries, and as pickup orders are mostly waste and used equipment which is not critical considering production on board platforms. Two delay limits are tested for, 27 and 18 departures, corresponding to approximately 20 and 15 days respectively, as calculated in Chapter 7.

Case A model runs

Comparisons are made between subcases for the same parameter. The situations in case A are evaluated based on the number and length of the delays, the demand quantities for these, as well as the average waiting time of orders. In addition, the total number of no-shows for the period is recorded. The number of express departures differing in express 1500 and express 3000 are counted and compared for the different situations with changed priority percentages and delay limits, in addition to actual express demand. Outputs from the analyses are presented in the next section. The findings in case A form a foundation for case B, so the aim is to decide on a model that gives the best optimisation of the important performance parameters. The findings in A will determine which scenarios are the most accurate and truthful, and emphasis will be put on these. The complete list of possible model runs for case A is presented in Table 8-4.

Subcase $A.X$	No-show α	Emergency θ	Delay limit τ	Case situation $A.X(\alpha,\theta,\tau)$
A.0	0	0	∞	A.0 (0,0,∞)
	25 %	0	∞	A.0 (25,0,∞)
		50 %	∞	A.0 (25,50,∞)
			27	A.0 (25,50,27)
			18	A.0 (25,50,18)
A.1	0	0	∞	A.1 (0,0,∞)
	25 %	0	∞	A.1 (25,0,∞)
		50 %	∞	A.1 (25,50,∞)
			27	A.1 (25,50,27)
			18	A.1 (25,50,18)
A.2	0	0	∞	A.2 (0,0,∞)
	25 %	0	∞	A.2 (25,0,∞)
		50 %	∞	A.2 (25,50,∞)
			27	A.2 (25,50,27)
			18	A.2 (25,50,18)

Table 8-4: *Case A model runs*

8.2.2 Case B: Alternative policies

The actual effects of the alternative routing policies applied depending on the route level in use, are explored in the level 2 and 3 analyses. This is evaluated based on variations in important parameters compared to the factual situation using fixed routes and schedules.

Due to flaws related to onshore logistics, Petrobras sometimes plan to bring orders that do not show up. This is not known before it is too late to re-plan the vessel load, resulting in the vessel leaving port with an unnecessary low load compared to its capacity. Since this study is aware of the average share of orders that do not show up, alternatives to try and reduce the implied costs are tested for. Overbooking is considered as a means to improve the utilisation of vessels. Overbooking means intentionally selling more cargo space than the available capacity to compensate for no-shows, cancellations and other variations, and it is a common practice in air cargo planning. Planning is done for a different capacity than the actual. The case here may be compared to passenger overbooking, for instance as modelled by Kasilingam (1997), since the seat capacity of aircrafts is known with certainty like our vessel deck space. Oversale costs are incurred when the cargo booked exceeds the available capacity, and may include costs of shipping excess cargo through other carriers. Spoilage costs on the other hand are revenue lost by not filling the capacity due to showup short of the capacity (Kasilingam, 1997).

In case B, the cost function is set in case A. Hence, the parameters considered similar to the ones in case A are the no-show and emergency percentages, and the possible delay limit. In addition a new parameter is presented, namely overbooking, which is presented as the percentage exceeding capacity, as δ. The overbooking parameters takes the values $\delta = 0{,}5 \ldots 30$. Normally, it would not make sense to set the overbooking fraction higher that the no-show fraction as it does not make sense to plan on exceeding the capacity all the time. But due to the already frequent use of express vessels due to the large amount of emergencies, filling the express vessels with additional demand might actually have delay saving effect without resulting in additional express costs. With this in mind, testing for large overbooking percentages should be explored as well. As for case A, a single situation in case B is given with a complete case name on the form:

$$B.X(\alpha, \theta, \delta)$$

$B.Y$ represents a sublevel of case B, where $Y = 1$ and 2 for sublevels 1 and 2 respectively. In addition to different overbooking percentages δ and the model level evaluated, each sublevel differs in the parameter reductions explored. As in case B, α and θ represent no-show and emergency percentages. Note that the delay limit for normal orders, τ, is not included her, as this parameter is settled in case A The sublevels are described in more detail in the following.

B.1: Alternative policies in the factual situation

In Case B.1 an overbooking policy is added to the order service currently yielding at Petrobras, where 25 % and 50 % of orders are no-shows and emergencies respectively. To make the model realistic it is assumed that if the actual orders at the port ready to be loaded exceed the vessel capacity even when accounting for orders that do not show up, the excess quantities have to be transported out that day all the same. For this, an unplanned express departure is required, where the excess capacity is added to the express demand presented in case A. An express departure has a high cost, and the aim is to see whether it may still be profitable compared to the alternative where nothing is done as an action against no-shows, and larger spoilage costs are incurred. If an express departure is already conducted parallel to the given scheduled order due to the delivery or pickup of unserved emergency orders, the excess demand is added to the express demand. Hence, as an express vessel might already be conducted in the yielding departure, excess demand does not necessarily induce any additional express costs. However, this depends on the order service for the current departure, where an express voyage without overbooking is not always the case.

B.2: Improving other parts of the supply chain

The previous analyses had the factual situation in focus, with 25 % no-shows on average. Another approach is now chosen, namely to examine the impact if Petrobras were able to reduce the share of no-shows by improving other parts in the supply chain, such as better communication and enhanced onshore transport solutions. In addition to examine the potential if such a reduction would occur, overbooking should be explored as well. In case B.2, lower overbooking percentages are investigated, to meet the corresponding reduction in no-shows from 25 % to 15 %.

Case B model runs

Case B returns the same output as for case A, summing the delays, overdue demand quantities, average waiting time, in addition to the number of express departures and express demand. As for case A, the total number of no-shows for the period is recorded. No-shows are only generated and counted for orders that were supposed to be distributed according to the optimal model solution for the current period. The demand in excess of the ordinary vessel capacity is also noted, giving the amount of express demand that is due to excess capacity when overbooking is considered.

In addition, the variations in parameters may accumulate to changes in other parameters as well. For example, if Petrobras managed to improve their onshore logistics and correspondingly reduce their amount of no-show orders, reductions in the amount of emergency orders requested could potentially follow. Due to the current no-show fraction platforms do not secure on time delivery within reasonable time of actual required delivery date. This problem is one of the primary reasons for the large amount of orders currently being recorded as emergencies in SAP. Hence, investigating the potential if Petrobras managed to reduce their amount of emergency orders from 50 % to a "normal state" of 10 % may be implemented. A complete list of possible model runs for case B is presented in Table 8-5. The model runs conducted depend on previous output produced and the model level evaluated. Not all model runs are necessary at all three model levels.

Subcase $B.Y$	No-show α	Emergency θ	Overbooking δ	Case situation $B.X(\alpha,\theta,\delta)$
B.1	25 %	50 %	0 %	B.1 (25,50,0)
			5 %	B.1 (25,50,5)
			10 %	B.1 (25,50,10)
			15 %	B.1 (25,50,15)
			20 %	B.1 (25,50,20)
			25 %	B.1 (25,50,25)
			30 %	B.1 (25,50,30)
		10 %	0 %	B.1 (25,50,0)
			5 %	B.1 (25,50,5)
			10 %	B.1 (25,50,10)
			15 %	B.1 (25,50,15)
			20 %	B.1 (25,50,20)
			25 %	B.1 (25,50,25)
B.2	15 %	50 %	0 %	B.1 (15,50,0)
			5 %	B.1 (15,50,5)
			10 %	B.1 (15,50,10)
			15 %	B.1 (15,50,15)
			20 %	B.1 (15,50,20)
		10 %	0 %	B.1 (15,10,0)
			5 %	B.1 (15,10,5)
			10 %	B.1 (15,10,10)
			15 %	B.1 (15,10,15)

Table 8-5: *Case B model runs*

8.3 Model output

In the analyses for cases A and B the model is tested for different values of some parameters, and the aim is to look at how these changes affect some common output values. The measures in focus for both cases are *delay in periods*, *average waiting time*, *delayed demands*, *express deliveries* and *express demands*. The case B output includes all of the values mentioned above in addition to *excess demands* due to the implementation of overbooking. A short description of these parameters follows, including their meaning and how they are calculated.

Delay in departures is the total number of departures that orders are delayed in a year, computed by multiplying and adding up the number of orders waiting for different numbers of departures. A waiting departure accounts for the departure in which the vessel did not deliver a given order while being requested. Example data are shown in Table 8-6 where the number of orders waiting for certain number of periods is counted in Xpress. The *average waiting time* is found by dividing the delay in departures by the total number of orders generated during the year, which is 13 368 for the model runs. The measure is a basis for comparisons between case situations. Since average waiting time is calculated using the delay in departures, these measures both describe the time delay of orders and have identical patterns. Average waiting time is more intuitive and can be interpreted as the number of periods an average order has to wait before being served. For that reason, average waiting time is used when discussing the cases, and *delay in departures* is introduced as a common term in the comparisons as percentage changes will be equal for the two.

Number of periods	Number of orders	Total wait
1 departure	631	631
2 departure	168	336
3 departure	118	354
4 departure	192	768
5 departure	99	495
6 departure	4	24
Delay in departures		2 608
Average waiting time		0.238

Table 8-6: *Calculation procedure: Delay in departures and Average waiting time*

Delayed demands is the sum of all the demand quantities related to the specific orders waiting. For instance, if an order of 45 waits for two periods before being served, it is added to 90 in total. This is consequently a measure of total delay given in square meter departures.

Express deliveries give the number of express deliveries in total during the year for the different case situations. When emergency orders exceed their delay limit, an express departure has to be taken. Similarly when planned order demands for a vessel exceeds the capacity even after accounting for no-shows. This can only happen when an overbooking policy is applied, since the model would otherwise never plan on violating the capacity constraint for a vessel. The *excess demands* is the sum of the quantities in excess of the capacity that consequently have to be transported on express departures.

The case models were run for two different sets of random order generations to assure that the output pattern would be the same. The numbers summarised in Table 8-7 apply for all the case situations. All model runs can be found in Appendix G, though, with both random order generations tested.

Number of orders:	13 368
Demands for orders (in square meters):	367 887
Demands for deliveries (in square meters):	263 581
Demands for pickups (in square meters):	104 306

Table 8-7: *Numbers for the random order generation used*

When the voyages are taken into consideration, as in model levels 2 and 3, the total sailing distance within a year should be evaluated. A special emphasise will be given to cots at level 2, as the potential savings in travel distance and applied costs should be weighted against additional order delays and corresponding express leasing. Another output value is the total year lateness cost for orders. As lateness costs are merely estimates based on some given information in addition to assumptions, looking at these values are not enough to draw any conclusions. However, looking at how other costs like sailing costs and express costs change according to different parameters and how routes are operated could serve as an advantage. However, the output values mentioned above are based on the cost function and cover most changes. Nevertheless, all costs are presented in Appendix G.

Chapter 9

Computational study

In this chapter results from the analyses are presented and discussed, incorporating both the cases presented in Chapter 8 and the different model levels mentioned in the previous chapters. Summaries and main findings are stated. The chapter is divided into three sections, where the first section imitates the actual route policy applied at Petrobras using fixed routes and schedules. The sections following this present the analyses when alternative route policies are tested, using model levels 2 and 3. All models are simulated for a year in total, corresponding to 678 departures.

9.1 Level 1 analysis

In this section the analysis considering model level 1 is presented. The analysis is divided into a case A and a case B. As presented in the case introduction, special emphasise will be given to case A in level 1 compared to a case A in levels 2 and 3. The objective of case A is to imitate the factual situation as closely as possible, and different parameters for the remaining model runs and analyses will be settled here. This includes elements like no-shows, emergency orders and express policies. Case B however, is set for model level 1 alone to evaluate the potential of planning with overbooking and to explore the effect of improving other parts of the supply chain. Firstly, case A for level 1 is presented, before different finding sets the further progress of a case B analysis.

9.1.1 Case A analysis at Level 1

In the initial subcase for case A the simple rule first-come-first-served was tested where orders that have waited longer are prioritised compared to new requests. Such a rule is excluded in the first and second subcases. The cost functions are applied as described in Table 8-3. The aim of case A at level 1 is to get a better understanding of the situation as of today. As express vessels are frequently leased and emergencies are falsely requested, some underlying issues should be addressed.

The different subcases depending on the cost function will be referred to as case A.0, A.1 and A.2. Case situations are named as explained in the case description. As an example, a situation with a multi-element including time of lateness cost function, and with 25 % no-shows and 50 % emergency orders present is named A.2 (25,50,∞). All the output can be found in Appendix G.

Cost function evaluation

First-come-first-served is a service policy, where demands from platforms are attended to in the order that they are received at the logistics central, without other biases and preferences. Subcase A.0 serves as a basis, where the aim is to explore the value in implementing the first-come-first-served policy compared to optimisation models. In subcase A.1 however, the cost for orders not served in a possible period is initially dependent on the size of orders and is correspondingly much higher that the initial costs in subcase A.0. The data outputs for subcase A.0 and A.1 are summarised in the first and second row in Table 9-1, respectively. The output data for each of the two subcases are compared in the bottom row of Table 9-1, using subcase A.0 as a benchmark. Note that costs are not given here, as there is no relationship between the actual numbers used in the cost generation for the two subcases. Costs are given as a penalty for delays, and minimising the costs in the objective function implies minimising delays.

Case situation	Waiting time	Delay in departures	Delayed demands
A.0 (0,0,∞)	3.31	44 198	1 220 110
A.1 (0,0,∞)	3.30	44 167	1 216 496
A.1 vs. A.2 reductions		*0.07 %*	*0.30 %*

Table 9-1: *Level 1 subcase A.0 and A.1 output summary*

There are no large changes in the output between A.0 and A.1. The small changes are positive, meaning delay is reduced for most situations of A.1. Even if reductions are scarce, they establish that the first-come-first-served policy is not a leading strategy and will not improve the optimal planning. Hence, the policy will not be implemented for other cases of the analyses.

The last cost function tested puts additional weight on the actual time of delay. The output produced for subcase A.2 is summarised in Table 9-2, where it is further compared to subcase A.1 in the bottom row. The aim is to study the effect of weighting the costs according to the actual time of lateness to a larger distinct than just adding the same amount for each departure delayed.

Case situation	Waiting time	Delay in departures	Delayed demands
A.2 (0,0,∞)	3.30	44 160	1 217 784
A.2 vs. A.1 reductions		*0.02 %*	*(0.11 %)*

Table 9-2: *Level 1 case A.2 output summary*

As for the comparison between subcase A.0 and A.1, the differences are not substantial. The reduction in average waiting time is less than 0.02 %, illustrating the small effect that the additional weighing of departure delay applies. However, an increase by 0.11 % in demand delayed is produced.. Based on these small differences, it is determined that cost function 1 is slightly more optimal when solving a simple SOP. Cost function 2 will be disregarded for the remaining analysis at level 1.

However when routes are challenged in the later study, the actual numbers used considering the cost for order lateness are weighted against the distances travelled, where choosing an optimal cost function becomes more essential. Considering this, both cost functions 1 and 2 will be explored further in the level 2 and level 3 analyses.

Introducing no-shows

The next step when imitating the actual situation is to introduce no-shows, which currently constitutes 25 % of the orders planned served. Table 9-3 presents relevant data output when 25 % no-shows is added to subcase A.1, where the bottom row shows the increase in important parameters compared to a situation with no no-shows.

Case situation	Waiting time	Delay in departures	Delayed demands
A.1 (25,0,∞)	12.43	166 150	5 395 544
Increase from A.1 (0,0,∞)		*276.18 %*	*343.53 %*

Table 9-3: *Introducing no-shows*

The total number of no-shows generated is around 2 046, which corresponds to 25 % of the delivery orders. The average waiting time and delayed demands are approximately three-folded compared to the situation without no-shows present. An order now has to wait for a week on average for service. A high increase here is however anticipated. When 25 % of orders do not show up in port in time for departure, additional delays of 7.5 departures for 25 % of orders are expected, as each platform is only served two times in the duration of 13 departures. In addition, the capacity becomes more evident in this case situation. The capacity is set to serve most orders assuming all planned orders are shipped during their corresponding departure. It does not cope the 25 % order increase of the $Active$ set for each departure, which follows no-shows.

As can be seen in Appendix G, orders wait up to 121 departures before scheduled vessel service in the case situation with no-shows present. This number is extremely high and of course not realistic when orders are requested to keep a continuing production operation on offshore facilities. Based on the findings above, one can understand the frequent leasing of express vessels, as the scheduled vessels do not seem to serve orders in a satisfying way when as much as 25 % of orders are no-shows.

Express policy

As earlier mentioned 50 % of all orders registered in SAP are labelled emergencies and have to be served within 8 departures. If the scheduled departures are not able to meet an emergency order within the given time limit, an unplanned express is conducted where additional costs apply. Table 9-4 summarises important data output when 25 % and 50 % of orders are no-shows and emergencies respectively. As both the current amounts of no-shows and emergencies are added here, case situation A.1 (25,0, ∞**)** illustrates the factual situation assuming no additional vessel policies are applied for normal orders. As one can see from the output produced, the fixed departure schedule is not able to meet all emergencies, and as much as 520 express 1500 are leased in a year. This corresponds to approximately 0.77 express departures for each scheduled departure on average, followed by express costs of $ 182 000 000 as found in Appendix G.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands
A.1 (25,50,∞)	520	0	32 268	6.55	87 588	2 737 780
Increase from A.1 (25,0,∞)	*520*	*0*	*32 268*		*47.28 %*	*49.26 %*

Table 9-4: *The factual situation*

Note that this policy assumes that decisions concerning the use of express vessels are made for each departure. This seems reasonable considering the frequent leasing of express without valuing efficient order allocation, which is currently the case. Emergency demand not met within the time limit has critical impact on the production flow, and express presently seem to be issued without regard to the costs that apply.

The bottom row in Table 9-4 shows the reduction in important parameters when 50 % or orders are prioritised and served as emergencies compared to the same situation with 0 % emergencies. Increases in delays of 47 % and 49 % considering waiting time and demands respectively, are present, which is not surprising given that 50 % of orders are guaranteed served within 8 departures. The average order wait for 6.55 departure while 2 737 780 square meter demand is delayed. By viewing the complete output in Appendix G, orders might risk up to 76 departures of delay. Considering this one can easily understand the amount of emergency requests that follow, where operators requesting order supply cope with frequent delays.

In addition, as 520 express 1500 serve 32 268 square meters of demand during a year, the average demand on each express departure corresponds to 62 square meters although an express 1500 offers a capacity of 240 square meters. Taking notion of this, expanding the express policy applied to consider normal orders as well could potentially be valuable. Output for case situations where delay limits are set to 27 and 18 departures for normal orders are presented in Table 9-5.

Case situation	Express		Express demand	Waiting time	Delay in departures	Delayed demands
	1500	3000				
A.1 (25,50,27)	540	1	34 942	5.26	70 360	2 106 288
A.1 (25,50,18)	566	1	37 340	4.77	63 700	1 855 840

Table 9-5: *Level 1 express policy testing for normal orders*

Some increases concerning the number of express vessels are produced in Table 9-5. When the delay limit is set to 27 departures (20 days), 21 additional express vessels are leased including 1 express 3000. Similarly for a delay limit of 18 departures (15 days), 46 and 1 additional express 1500 and 3000 are leased, respectively. A lot of saving in order delays is however evident when considering comparisons to the situation with no express policy for normal orders applied, which is presented in Table 9-6. The average waiting is reduced by 19.7 % and 27.3 % with delay limits of 27 and 18 respectively, while total demands are reduced by 23.1 % and 32.2 % correspondingly.

Reductions compared to A.1 (25,50,∞)

Capacity situation	Express demand	Delay in departures	Delayed demands
A.1 (25,50,27)	*(8.3 %)*	*19.7 %*	*23.1 %*
A.1 (25,50,18)	*(15.7 %)*	*27.3 %*	*32.2 %*

Table 9-6: *Comparing level 1 subcase A.1 with different express policies for normal orders*

There exists potentially large savings using different express policies, as express vessels are already leased serving emergencies, and as additional express demand does not seem to exceed the capacity of already utilised express vessels to a large distinct. However, any conclusions regarding such a policy can not be settled, as they are to the author's knowledge non-existing. Following this, the policies tested will not proceed into a case B at level 1, as the aim is to see the implications of overbooking in addition to reductions in no-shows and emergencies against the present situation. Nevertheless it is interesting to see the usefulness of different policies, which gives a clearer understanding of reasons to why Petrobras currently operates with their frequent express leasing.

9.1.2 Case B analysis at Level 1

As mentioned in the case description, case B is divided into two subcases differing in how the no-show fraction is varied. In the first subcase B.1, 25 % no-shows and 50 % emergency orders are applied, imitating the factual situation at Petrobras. Subcase B.1 has been tested with five different overbooking percentages: 5, 10, 20, 25 and 30 %. The same tests are done in subcase B.2, where no-shows comprise 15 % of orders. In addition, subcase B.2 is tested with an emergency fraction of 10 %. This reduction corresponds to a normal state, which could potentially be a further progress if Petrobras were able to regain trust among participants in the supply chain. All outputs can be found in Appendix G.

The variations within each subcase differ based on the overbooking percentages. The subcases are named as previously defined in the case description, so a situation with 25 % no-shows, 50 % emergency orders and 10 % overbooking is referred to as B.1 (25,50,10). The costs are updated and calculated according to the cost function in subcase A.1.

B.1: Overbooking in the factual situation

Table 9-7 shows the output produced when different overbooking strategies are applied to the level 1 situation with 25 % no-shows and 50 % emergencies. Note that case situation B.1 (25,50,0) is the same case situation A.1 (25,50,∞) in Table 9-4. The costs in the objective function do not form a basis for interpretation at level 1, but are merely the means to ensure that the model runs as intended. Costs are hence omitted from the level 1 case B analysis. An additional measure of interest when overbooking is used however is the total capacity exceeded. This is the demand that still exceeds capacity when no-shows become known, which is further served with express. Without overbooking there will naturally not be any capacity exceeded, since express deliveries are only used when the scheduled departure delivery quantities exceed the actual capacity for the vessel.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands	Capacity exceeded
B.1 (25,50,0)	520	0	32 268	6.55	87 588	2 737 780	0
B.1 (25,50,5)	517	0	30 102	5.46	72 988	2 191 009	166
B.1 (25,50,10)	534	0	30 259	5.01	66 949	1 990 777	496
B.1 (25,50,20)	509	0	28 988	4.50	60 222	1 734 156	1 668
B.1 (25,50,25)	493	2	30 221	4.36	58 336	1 659 730	2 964
B.1 (25,50,30)	524	3	32 513	4.30	57 463	1 634 415	3 793

Table 9-7: *Level 1 subcase B.1 model output*

As mentioned, the cost in itself is not of importance in case B. Comparing the different overbooking strategies applied, the delay and express demand are interesting factors to draw attention to. Table 9-8 is a summary of comparisons made between the case situations, where reductions are given for changes from the benchmark of no overbooking to 5, 10 and further up to 30 % overbooking. When the overbooking percentage is set equal to or more than 20 %, the time delay and demand delay are reduced by more than 30 %. The difference is large, and the impact is similarly larger with increasing overbooking factor. Without overbooking, the orders are expected served after 6.55 departures of waiting on average. When more than 20 % overbooking is used, the expected wait is reduced to less than 4.50 departures. These numbers are worth noticing, as they represent the upside from planning with overbooking. Due to the fact that 50 % of orders are prioritised without regards to order size, planning with overbooking gives room for additional size prioritisation. This is to a large distinct lacking with no overbooking, as emergency orders overshadow this potential when capacity is scarce. Correspondingly the quantities decrease for the remaining unserved orders, resulting in additional savings for larger overbooking percentages.

Reductions compared to B.1 (25,50,0)

Capacity situation	Express demand	Delay in departures	Delayed demands
B.1-620 (25,50,5)	*6.71 %*	*16.67 %*	*19.97 %*
B.1-620 (25,50,10)	*6.23 %*	*23.56 %*	*27.28 %*
B.1-620 (25,50,20)	*10.16 %*	*31.24 %*	*36.66 %*
B.1-620 (25,50,25)	*6.34 %*	*33.40 %*	*39.38 %*
B.1-620 (25,50,30)	*(0.76 %)*	*34.39 %*	*40.30 %*

Table 9-8: *Comparing level 1 subcase B.1 with different overbooking strategies*

There is a trade-off between the savings discussed so far shown in Table 9-8 and the following increase in the number of express demand and express deliveries required following demand exceeding the capacity, as shown in Table 9-7. As earlier mentioned the number of express vessels conducted is not necessarily set as the ones showed in Table 9-7. This all depends on the current policies Petrobras operates with regarding the frequency in which express vessels are leased. An important parameter of comparison however, is the express demand for each case situation. One would expect that the total amount of express demand would increase with increasing overbooking percentages, as the capacity exceeded increases correspondingly. However, this does not seem to be the case with overbooking percentages equal to or less than the no-show fraction. Without overbooking present approximately 9 % of orders are served with express (express demand 32 268 of total demand 367 887 square meters). As the total amount of express demand is in fact reduced, it is evident that additional capacity in the planning results in better utilisation of the scheduled vessels. The largest reduction is found when 20 % overbooking is used, with a corresponding reduction of 10.16 % in express demand and additional large savings in order delays of 31.24 % and 36.66 % considering waiting in departures and size in square meters, respectively.

Switching focus to the actual express departures conducted assuming the policy implemented to be realistic, additional express savings are present when 25 % overbooking is planned for. With 25 % excess capacity planned, 493 and 2 express 1500 and 3000 are conducted respectively, while 509 express 1500 are issued when 20 % overbooking is used. Implementing 30 % overbooking is irrelevant in comparison, as larger overbooking percentage results in more express demand, and small, almost insignificant additional reductions in delays.

An understanding is now obtained considering the impact of overbooking on the factual situation at Petrobras. Summarised there is a great potential for improvements with this alternative approach to planning, but also a trade-off considering costs related to express deliveries when the overbooking percentage exceeds no-shows. In addition, the cost of express departures must be weighed against the inconvenience of delays for orders. That is, overbooking costs calculated as express costs versus spoilage costs. This evaluation is left to the decision makers, but the findings could be a solid starting point with quantified impacts presented for the alternative decisions. A deeper study of the costs or possible solutions besides express departures may be done for a final decision. However, it is reasonable to assume that 20-25 % overbooking is a sensible strategy, as the increase in efficiency for order serving is very high while the number of express deliveries is actually reduced bearing in mind that the time is of an entire year.

An additional study could be to do the same analysis with the use of an express policy for normal orders as well. However, this does not seem necessary, as the average waiting of orders is already faced with large reductions. Looking at the complete output summary when 20 % overbooking is used, 38 orders are delayed for more than 27 departures. A further express policy may overshadow the overbooking potential, which is the actual aim of the study here. Emphasising this in combination with the uncertainty of additional policies, it is chosen not to proceed with such an analysis. Model runs were nevertheless conducted, and the output is presented in Appendix G.

B.2: Reduction of no-shows in the factual situation

The previous analyses had the factual situation in focus, with 25 % no-shows on average. Another approach is now chosen, namely to examine the impact if Petrobras were able to reduce the share of no-shows by improving other parts in the supply chain, such as better communication and enhanced onshore transport solutions. As for the situations above the analyses are done with cost function 1, where overbooking is included. The first line in Table 9-9 presents the results for a year with 15 % no-shows. The number of no-show orders generated in this case is around 1 248.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands
B.2 (15,50,0)	401	0	18 382	4.81	64 270	1 912 562
Reductions from B.1 (25,50,0)	*119*	*0*	*43.03 %*		*26.62 %*	*30.14 %*

Table 9-9: *Level 1 subcase B.2 output*

The bottom row in Table 9-9 compares the situation with 15 % no-shows with the factual. The average waiting time is reduced by approximately 27 %, while demand quantities faces a reduction of 30 %. In addition, the total express demand is reduced by 43 %, where the number of express is reduced correspondingly from 520 to 401 departures in a year. Based on these findings, it is clear that there are great potential gains from reducing the late arrivals of orders to port. The purpose here is foremost to examine the impact of reducing no-shows, and it is not as valuable to study different overbooking strategies as in B.1. Overbooking is however included, as additional savings could result. It is not appropriate to analyse the case of overbooking exceeding the no-shows percentage of 15 %, as this was proven ineffective in subcase B.1. The output produced when implementing overbooking strategies of 5, 10 and 15 % is given in Table 9-10.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands	Capacity exceeded
B.2 (15,50,5)	408	0	18 553	4.09	54 623	1 560 778	239
B.2 (15,50,10)	410	0	18 283	3.96	52 900	1 495 384	1 317
B.2 (15,50,15)	411	0	20 409	3.86	51 637	1 447 632	2 524

Table 9-10: *Level 1 subcase B.2 model output with different overbooking strategies*

Using the output produced in Table 9-10, reductions compared to a benchmark of no overbooking and 15 % no-shows is calculated in Table 9-11. By viewing the reductions, the only case situation where a reduction in express demand is actually present is with the use of 10 % overbooking. In this case situation the time of delay in departures is reduced by almost 18 %, while demand delayed in square meters is reduced by approximately 22 %. Some additional reductions in delays are present when the overbooking percentage is set equal to no-shows, namely 15 %. However, as the additional reductions are small compared to the fact that express demand has increased by more than 10 % due to excess capacity, the most reasonable strategy seems to be 10 % overbooking in this setting.

Reductions compared to B.2-620 (15,50,0)

Case situation	Express demand	Delay in time	Delayed demands
B.2 (15,50,5)	(0.93 %)	15.01 %	18.39 %
B.2 (15,50,10)	0.54 %	17.69 %	21.81 %
B.2 (15,50,15)	(10.03 %)	19.66 %	24.31 %

Table 9-11: *Comparing level 1 subcase B.1 with different overbooking percentages*

Following the improvements in order delays when no-shows are reduced to 15 %, trust could potentially be gained between the relevant participants regarding order service with the prospective of reducing the number of emergency orders requested back to it normal state, namely 10 %. With such a possibility at hand, looking at its potential could create valuable information for decision makers. Table 9-12 shows the output produced when the emergencies requested are reduced to 10 %, where the bottom row compares the numbers against the situation with 25 % no-shows and 50 % emergencies.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands
B.2 (15,10,0)	108	0	3 688	6.63	88 657	2 772 304
Reductions from B.1 (15,50,0)	*293*	*0*	*79.94 %*		*(37.94 %)*	*(44.95 %)*

Table 9-12: *Level 1 subcase B.2 output with 10 % emergencies*

When the number of emergencies is reduced from 50 % to 10 %, the express policy considering that orders delayed for more than 8 departures are served with an express vessel only accommodates 10 % of orders. Correspondingly, it is expected that delays will increase while the amount of express demand is reduced, as fewer orders are served with express. By looking at the comparison presented in Table 9-12, the total express demand is reduced by approximately 80 %. This however, should be balanced against the fact that time and demand of delay have increased by 38 % and 45 %, respectively.

Implementing overbooking could potentially reduce some of the delays, as previous experience has proven. Table 9-13 present the output when overbooking strategies of 5, 10 and 15 % are implemented to the situation with 15 % no-shows and 10 % emergencies.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands	Capacity exceeded
B.2 (15,10,5)	115	0	3 534	5.27	70 515	2 119 095	347
B.2 (15,10,10)	137	0	5 195	4.24	56 707	1 620 918	1 685
B.2 (15,10,15)	139	0	6 830	4.13	55 163	1 570 453	3 302

Table 9-13: *Level 1 subcase B.2 model output with 10 % emergencies*

The case situations in Table 9-13 are compared to the same situation with no overbooking in Table 9-14. Putting more weight on the delay compared to express, as express demand is already faced with significant reductions with 10 % emergencies applied, most savings are present when 10 % overbooking is applied. Although express demand is faced with an increase of approximately 41 % square meters, 10 % most reasonable considering reductions in order delay. Using an overbooking fraction equal to no-shows is not efficient, as reductions in delays are approximately the same as for 10 % overbooking while the increase in express demand is more than doubled.

Reductions compared to B.2 (15,10,0)

Case situation	Express demand	Delay in departures	Delayed demands
B.2 (15,10,5)	4.18 %	20.46 %	23.56 %
B.2 (15,10,10)	(40.86 %)	36.04 %	41.53 %
B.2 (15,10,15)	(85.20 %)	37.78 %	43.35 %

Table 9-14: *Comparing level 1 subcase B.2 with 10 % emergencies and different overbooking strategies*

Taking 10 % overbooking further in this subcase, it would be interesting to calculate the actual savings if Petrobras could reduce their amount of no-shows and emergencies to 15 % and 10 % respectively in addition to the use of a 10 % overbooking strategy. Such a comparison to the factual situation is presented in Table 9-15.

Reductions compared to B.0-620 (25,50,0)

Case situation	Express demand	Delay in time	Delayed demands
B.2-620 (15,10,10)	83.90 %	35.26 %	40.79 %

Table 9-15: *Comparing level 1 subcase B.2 with 10 % overbooking to the factual situation*

As presented in Table 9-15, large potential reductions are evident. The average waiting time is now reduced from 6.55 to 4.24 departures, while the total demand delayed is reduced with approximately 41 % square meters. However, the largest savings concern express demand and the number of express vessels conducted, where express demand is reduced by nearly 84 %. This results in only 137 express vessels compared to the present situation with 520 express 1500. The factual situation sets the express costs to $ 182 000 000, and the proposed situation reduces the costs to $ 47 950 000. This is a large amount of money saved, while the potential of reducing order delays is present as well. With the proposed case situation orders have to wait up to 50 departures before served, and the average order is served within 4.24 departures. As each platform is visited approximately two times in the duration of 13 departures, an average waiting time 4.24 is fairly reasonable if the aim is to gain trust between participants in the value chain with the use of fixed routes and schedules.

No analysis is of course needed to state the fact that no-shows should ideally be non-existing. Still, it is useful to quantify the impacts as done above, to clearly show the potential. Improvements in the relevant parts of the supply chain may be both costly and require internal changes, but knowing the benefits could act as an incentive to make an effort in the case.

9.2 Level 2 analysis

In this subchapter the analyses for model level 2 where flexibility is added to the predetermined and fixed routes are presented. As for level 1 the analyses is divided into a case A and a case B. Case A is shorter in comparison, as most parameters like the vessel capacity, no-shows and express policies were settled in the level 1 analysis. The cost function used is based on the level alone however, as the objective functions differ in the routing level applied. Actual routes are stressed at level 2, where distances travelled are taken into consideration. Following this, choosing a cost function that emphasizes order service in the best possible manner becomes even more evident compared to level 1. If lateness costs are set small relative to travel costs, increasing delays may result in addition to more frequent express leasing. Hence, the cost function is settled based on level 2 alone, which is the intention of case A. Nevertheless, most of the study at level 2 alone is presented in case B, where overbooking and reductions in no-shows and emergency orders are explored further. The situations valued most relevant are compared to the present situation using fixed routes and schedules. The purpose is to calculate the potential cost savings and delay outcome when route flexibility is added to the problem.

The term “flexibility” in this setting means the option to exclude visitation of platforms already existing in the predetermined route. However, it does not mean any extra order service considering a single departure, as no additional platforms can be visited than the ones already existing in the predetermined route. Following this, no reductions in order delay alone are expected without the cost of increasing other parameters. The study now becomes to see whether cost savings could potentially be present by including the actual costs saved with journeys shortened balanced against additional delays and/or express. This clearly depends on the costs used in the optimisation. Travelling costs are pretty much safe, as they illustrate real costs currently applied at Petrobras. The express costs are also based on directs cost. These costs however, assume the applied express policy being factual, meaning that decisions concerning express leasing are made for a single departure. So far this has made sense, and there are no reasons to believe that they should not be applicable in this setting as well. Costs coupled to order delays on the other hand, are fictive and valued based on the author’s subjective opinion. With this is mind, it is important to balance the potential cost savings in travel distance against the possible increases in order delays and/or extra express leasing and demand. Hence, a comprehensive analysis considering actual costs is used in this setting.

9.2.1 Case A analysis at Level 2

It is easy to see that the first-come-first-served policy will not be of any value here, as each order is initialised with an insignificant amount giving no incentive to serve orders in their first departure considering the corresponding voyage costs that apply. However, both cost functions 1 and 2 as presented in subcases A.1 and A.2 at level 1 respectively, are given further attention here. As in the level 1 analysis the different subcases mentioned will be referred to as subcase A.1 and A.2, respectively. Case situations are named as explained in the case description. As an example, a situation with a multi-element cost function stressing time of lateness that in addition includes no-shows and emergency orders is named A.2 (25,50,∞).

Even though actual cost are given special attention at level 2, they are disregarded from the case A analysis as the objective in this sections is to determine the most optimal cost function considering order service, distances and express usage. An additional parameter showing the complete travel distance is included however, as an important element of this study is to evaluate the potential saving if the option to exclude visitation of some platforms in a yielding voyage is present. Travelling costs are not present, as the distances travelled measures the same difference. Actual cost will be present in the next section, where the potential savings are calculated. Nevertheless, all costs considering case A can be found in Appendix G.

Model output using both cost functions is presented in Table 9-16, where the bottom row shows the potential reductions when comparing cost function 2 to cost function 1. As the comparison presents, there is nearly no savings present when cost function 2 is implemented, which further illustrates that no potential gain can come from additional emphasise on actual time of delay in this setting. Even if the differences are small, they are all increasing. With cost function 2 applied 10 additional express leasing are present, orders wait for longer and more demand are delayed.

Case situation	Express 1500	3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance
A.1 (25,50,∞)	530	1	34 021	4.76	63 688	1 849 594	336 606
A.2 (25,50,∞)	540	0	34 076	4.78	63 833	1 861 702	337 448
A.2 vs. A.1 reductions	*(10)*	*1*	*(0.16 %)*		*(0.23 %)*	*(0.65 %)*	*(0.25 %)*

Table 9-16: *Level 2 case A output*

One would expect an increase in distances travelled to be present in subcase A.2, as more weight is put on order delay rather than sailing here. The output produced shows a slight increase of 0.25 %, indicating that both cost functions puts more weight on the actual order service rather than sailing. This seems reasonable considering the risky outcome when orders are delayed for long. Based on this comparison, a cost function equal to the one presented in subcase A.1 will be implemented in the case B analysis at Level 2.

9.2.2 Case B analysis at Level 2

With the cost function settled, the analyses when flexibility is added to the routing aspect continues. As in level 1, case B is divided into two subcases differing in how the no-show and emergency fractions are varied. However, in this case the output produced is compared to the factual situation using fixed routes and schedules. The analysis is based on finding the potential gains by adding flexibility, where possible overbooking strategies and reductions in no-shows and emergencies comes in addition to this. In the first subcase B.1 the factual orders service situation at Petrobras is applied to the situations with flexible routes, where no-shows and emergencies are set to 25 % and 50 % respectively. Subcase B.1 is tested with two different overbooking percentages: 20 and 25 %. In subcase B.2 the no-shows comprise 15 % of orders. Situations with 50 and 10 % emergencies are tested, in addition to a 10 % overbooking strategy. All output is found in Appendix G.

The subcases are named as previously defined in the case description, similar to the level 1 situations. So a situation with 25 % no-shows, 50 % emergency orders and 20 % overbooking using level 2 routes is referred to as level 2 B.1 (25,50,20). The costs are updated and calculated according to the cost function in subcase A.1.

B.1 Flexible routes in the factual order service situation

As mentioned, the most important study here is to address the affect when flexibility is added to the fixed routes currently in use. Table 9-17 presents the output produced when applying the proposed routing policy to the factual order service situation. The total number of no-shows generated is around 2 037, which corresponds to 25 % of the delivery orders. The output measures analysed were defined in the first subchapter of the analysis. In addition, as the potential gain from adding flexibility is reduced sailing, this measure is included under “Travel distance”. The objective function now takes into account the actual distances travelled for each voyage, and differences can be found her in addition to order delay and express use.

Case situation	Express 1500	3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance
B.1 (25,50,0)	530	1	34 021	4.76	63 688	1 849 494	336 606
Reductions from level 1	*(10)*	*(1)*	*(5.43 %)*		*27.29 %*	*32.44 %*	*3.16 %*

Table 9-17: *Level 2 subcase B.1 output*

The bottom row in Table 9-17 presents reductions when comparing level 2 to the present routing situation using the same input. The comparison is first and foremost presented without the proposed overbooking policy, as no such strategy currently exists regarding order supply at Petrobras. With a first glance of the output produced, large potential savings considering order delays seem to apply. As much as 27.29 % and 32.44 % reductions considering waiting and size, respectively are present. The explanation of the large reduction in order delay does not come from additional order service adding flexibility to routes, as explained above. Express demand has increased by 5.43 % followed by 11 additional express departures. This naturally affects order delays. The objectives now values the distances travelled, and will seek to reduce this amount in situations were it seems reasonable to exclude platform service at the gain of travelling less. In these situations orders wait for longer, which is followed by increased express use.

However, the question that remains is the actual benefit of sailing and serving less with scheduled vessels at the cost of added express. One can not evaluate the potential without considering costs in this setting. Table 9-18 shows the corresponding costs saving in express usage and distances travelled, which are summed up to a total saving in the rightmost column. Note that the express costs here is not grounded on the actual express demand served, but is calculated based on the number of express vessels conducted. As presented in Table 9-4 in Section 9.1, 520 express 1500 were used in the factual situation with fixed routes, assuming that the applied express policy demonstrates the factual situation.

Cost savings compared to level 1 B.0 (25,50,0)

Case situation	Express cost	Travel cost	Total saving
Level 2 B.0 (25,50,0)	($ 3 990 000)	$ 4 618 740	*$ 628 740*

Table 9-18: *Cost savings from using flexible routes*

One would think that a reduction in travel distance for a single departure alone would have little effect on the large amount of money present. However summing for a year in total, small savings become significant. Table 9-18 calculates a total saving of $ 628 740 when additional express costs are subtracted. This is not an especially huge amount considering the corresponding total travel costs of $ 141 374 520. Nevertheless, it illustrates that when travel costs are saved, it covers the additional express costs following reduced order delays. One could settle with this, as the presented analysis shows great gains by adding voyage flexibility. However, the level 1 study revealed that overbooking strategies when planning for 20 % and 25 % additional capacity were useful. Table 9-19 shows the output when overbooking strategies are added to the simulation using flexible routes.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance	Capacity exceeded
B.1 (25,50,20)	534	0	33 192	4.58	61 240	1 772 244	335 782	159
B.1 (25,50,25)	520	1	32 310	4.61	61 580	1 775 233	336 592	277

Table 9-19: *Level 2 subcase B.1 model output with different overbooking strategies*

By looking at the data produced, it is evident that overbooking strategies are applicable in this setting as well. The numbers of express vessels leased are reduced compared to the situation with no overbooking. In Table 9-20 the actual reductions are calculated against the present situation with fixed routes. As the comparisons show, introducing overbooking reduces some of the problem concerning additional express use. With as much as 25 % overbooking present, express demand is now increased by a smaller fraction of 0.13 % transported by 1 additional express 3000, whereas the voyages are shortened by 3.17 %. In addition, even more savings in delays are present, with 26.69 % and 35.16 % in departures and square meters respectively. However, the largest saving considering order delay is produced when 20 % overbooking is planned for. Consequently, additional express demand is reduced by less.

Reductions compared to level 1 B.1 (25,50,0)

Case situation	Express demand	Delay in departures	Delayed demands	Travel distance
Level 2 B.1 (25,50,20)	(2.86 %)	30.08 %	35.27 %	3.40 %
Level 2 B.1 (25,50,25)	(0.13 %)	29.69 %	35.16 %	3.17 %

Table 9-20: *Comparing level 2 subcase B.1 with the factual situation*

To evaluate the total effect of overbooking strategies, a cost analysis must be supplemented. Table 9-21 presents potential cost savings when overbooking strategies of 20 % and 25 % are applied, respectively. 25 % overbooking result in $ 4 134 260 saved. With 20 % overbooking, only $ 64 820 is saved even if the scheduled vessels travel less. Additional express is induced with more exceeded capacity however, which is costly and outweighs most of the saving in sailing.

Cost savings compared to level 1 B.0 (25,50,0)

Case situation	Express cost	Travel cost	Total saving
Level 2 B.0 (25,50,20)	($ 4 900 000)	$ 4 964 820	*$ 64 820*
Level 2 B.0 (25,50,25)	($ 490 000)	$ 4 624 260	*$ 4 134 260*

Table 9-21: *Cost savings from using flexible routes and different overbooking strategies*

The output results clearly show large potentials when flexibility is added to the fixed routes currently yielding at Petrobras. Costs are saved while service delays are reduced. In addition, further savings a present with the use of different overbooking strategies. Choosing the most optimal method however, where cost savings are balanced against order delays, are up to the decision makers.

B.2 Reduction of no-shows in addition to flexible routes

With flexibility added to the given and predetermined route, the previous analysis assumed the presence of 25 % no-show orders on average. As for level 1, this percentage could potentially be reduced if Petrobras were able to improve other parts of the supply chain in addition to the route policy. The impact of such a reduction is investigated in the following. Table 9-22 gives the output produced and compares it to the factual situation using fixed routes. The number of no-show orders are 1 237, corresponding to 15 % of delivery orders.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance
B.1-620 (15,50,0)	427	0	20 758	4.04	53 953	1 532 415	335 393
Saving from level 1	*93*	*0*	*35.67 %*		*38.40 %*	*44.03 %*	*3.51 %*

Table 9-22: *Level 2 subcase B.2 output*

As expected, reducing no-shows results in less order delay, where savings of 38.40 % and 44.03 % in departure and square meters respectively apply. In addition, 93 express departures and corresponding costs are avoided, followed by 35.67 % less express square meter demand. However, to get the complete effect of the no-show reduction in addition to the alternative routing policy, a cost saving calculation is addressed. This is presented in Table 9-23, where traded transportation and express cost sums to $ 37 678 260 saved. Needless to say, large potential savings are present, where millions of dollars could be saved if the suggested improvements were present. As mentioned, these cost savings are further followed by large reduction in order delay.

Cost savings compared to level 1 B.1 (25,50,0)

Case situation	Express cost	Travel cost	Total saving
Level 2 B.2 (15,50,0)	$ 32 550 000	$ 5 128 260	*$ 37 678 260*

Table 9-23: *Cost savings from using flexible routes and reducing no-shows*

Overbooking may be included here as well, but as the intention of this subcase is to evaluate the effect of improving other parts of the value chain, in addition to flexible voyages, it is left with this for now. In addition, as the use of overbooking had a similar effect in subcase B.1 for level 2 as in level 1, is is safe to assume that a related effect is present her as well. Another implication that should be attended however is to evaluate the further impact if the number of emergencies present could be reduced to its normal state of 10 %, as this is considered to be the next step when no-shows faces reductions. The corresponding output is given in Table 9-24.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance
B.2 (15,10,0)	173	0	6 368	5.38	71 861	2 156 517	334 261
Saving from level 1	*347*	*0*	*80.27 %*		*17.95 %*	*21.23 %*	*3.84 %*

Table 9-24: *Level 2 subcase B.2 output with 10 % emergencies*

The bottom row in Table 9-24 shows a comparison to a benchmark using fixed routes in the factual situation. Large reductions in order delay are still evident, even if they are not as severe as when 50 % of emergencies were requested. This is as expected, as a delay limit and further express policy is only applied to 10 % of orders. The upside of the emergency reduction however, is the extreme decline in the number of express vessels requested, corresponding to an 80 % decline in square meter demand. In addition, the total year distances travelled are reduced further. When only 10 % of orders are given special attention, more consideration is distributed to other aspects of planning, like vessel utilisations and voyage optimisation. This is evident, as reductions follow in both of these measures. Following this, a costs saving is anticipated. This is calculated in Table 9-25.

Cost savings compared to level 1 B.1 (25,50,0)

Case situation	Express cost	Travel cost	Total saving
Level 2 B.2 (15,10,0)	$ 121 450 000	$ 5 603 260	*$ 127 053 260*

Table 9-25: *Cost savings from using flexible routes and reducing no-shows and emergencies*

It was mentioned earlier that effect of overbooking here is assumed to have a similar effect as in the level 1 analysis. Investigating the effect of using flexible routes showed a lot of potential in subcase B.1, with further reductions and savings following in this subcase. However, the evaluation that remains is to see whether the effect is still as evident when additional proposed improvements are addressed. Hence, the assumed "best" situation her should be evaluated against the "best" situation using fixed routes. This was presented in Table 9-14, where an overbooking policy of 10 % was applied in addition to the same amount of no-shows and emergencies as here. Table 9-26 presents the output using both model levels, where the bottom row shows potential savings.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance
Level 1 B.2 (15,10,10)	137	0	5 195	4.24	56 707	1 620 918	347 603
Level 2 B.2 (15,10,10)	143	0	5 362	4.45	59 440	1 714 190	334 431
Level 2 vs. Level 1 savings	*(5)*	*0*	*(3.21 %)*		*(4.82 %)*	*(5.75 %)*	*3.79*

Table 9-26: *Comparing subcase B.2 levels 1 and 2*

The only additional reduction evident when routes are made flexible is found in the distances travelled. The remaining parameters are better off using fixed routes. A cost evaluation is however needed, to see the additional cost saving that result from reducing distances against excess express use. This is calculated in Table 9-27.

Additional cost savings compared to level 1 B.2-620 (15,10,10)

Case situation	Express cost	Travel cost	Total saving
Level 2 B.2 (15,10,10)	($ 2 100 000)	$ 5 532 260	*$ 3 432 260*

Table 9-27: Additional *cost savings from using flexible routes compared to fixed*

The calculation in Table 9-27 results in a cost gain of more than 3.4 million dollars when flexible routes are in use. Hence, it is evident that the savings in vessel travel outweighs additional express departures. But even so, the use of fixed routes weighs more on actual order service, where reductions of 4.82 % and 5.75 % are present in departures and square meter demand, respectively. At this point however, balancing costs against service is up to the decision makers. It is important to note that the latter study assumes that a reduction in no-shows and emergency orders follow if trust between participant is created. In addition, the implementation of a 10 % overbooking strategy is present, which is not the case in the factual situation. It is however interesting to evaluate potential gains that could be obtained if flexibility is added, both in the factual order supply situation and when different policies and reductions are applied. Especially the study made in case B.1 showed large potential, where no additional improvements were applied. Savings in sailing outweighed additional express use in most situations, and reductions in order delay often follow.

Nevertheless, it seems that trust is a necessary requirement to make the proposed solution applicable all the same. When planning for a single departure alone, the purpose is to serve as many orders as possible. This method however, requires the decision maker to look further a head, where they in some departures have to plan for additional delays to create profit in the end. Savings will not be evident in a single departure alone. Confidence regarding its applicability is necessary, and it requires decisions makers to be consistent in their decisions throughout the planning horizon.

9.3 Level 3 analysis

In this section the analysis for model level 3 is presented. At level 3 routes are generated completely dynamic for each departure, restricted by orders requests and allowed voyage duration. Logistics are currently facing some internal uncertainties in the supply chain, which was a leading reason to why they implement fixed PSV routes and schedules. The strategy was implemented as a response to the lack of trust between supply chain participants, with the incentive to create reliability and predictability in order handling to avoid emergency requests from facilities. However, as the analysis in Section 9.1 illustrates, the issue still seems to exist considering the amount of no-shows and emergencies currently present. Considering this, the motivation for using fixed routes disappears, and lack of trust is still evident. As a response, the use of dynamic route generation is proposed as an alternative solution.

As in previous levels, the analysis is divided into a case A and a case B. The case A objective is to settle the best cost function coupled to inconvenience of delay, which is further implemented in proceeding simulations for a case B analysis. The cost function is chosen based on level 3 alone, without regards to previous studies. Choosing a cost function that emphasizes order service in the best possible manner becomes especially important here, as actual distances travelled are only restricted by the allowed voyage duration, as calculated in Chapter 7. Most of the analyses are however presented in case B. The purpose here is to calculate the potential improvements for when a routing problem is solved supplementary to the supply order problem at each departure. The effect of overbooking is tested, in addition to implementing possible reductions in no-shows and emergency orders assuming improvements in other parts of the supply chain.

The output measures used are presented in Chapter 8. Even though the actual distances travelled are part of the objective function at level 3, the corresponding costs that apply are not given the same amount of attention as in level 2. Predetermined routes and subset of platforms no longer restrict voyages, and potentially large reduction considering order delay is expected. Following this a more effective emergency service is anticipated, with less express leasing. Taking all of these expectations into considerations, it is assumed that the measures like express use, order delay and distances travelled are enough to investigate the effect. Even so, all costs are calculated and can be found in Appendix G.

As previous chapters explained, level 3 is divided into two sublevels 3.1 and 3.2, differing in platforms being allowed as second visit or not for separate pickup and delivery. Sublevel 3.2 allows two visits. When the model is run with a level 3.2 routing policy applied, the solutions time becomes an issue. Two separate nodes are now coupled to each platform, which is followed by a large increase in constraints and variables compared to previous models. Solving an optimization problem for each departure without applying a maximum solution time seemed nearly impossible. The model would run for several days, locked at specific departures where the problem solving was too complex. It was however evident that the duality gap quickly decreased within the first seconds of solving. As the duality gap measures the maximum relative deviation from optimality of the best feasible solution found (Pochet and Wolsey, 2000), close to optimal solving was obtained within the first minute. Based on this, a maximum solution time considering the solving for each departure was implemented to ensure that complete simulations could be obtained. Each simulation still had to run for numerous hours, even days in total, as 678 departures were aimed optimised. Nevertheless, close to optimal estimates were produced.

Different solution times were tested, where not surprisingly the uppermost limit of 15 minutes solving for each departure generated the best results. Hence, a solution time of 15 minutes is used in proceeding model output considering a level 3.2 routing policy. Supplementary, the model outputs with a solution time of 7 minutes are given in Appendix G. With a solution time present however, only close to optimal results could be gathered. This is an important factor to consider when further evaluating the effect of allowing two visits to the same platforms compared to other situations with optimal solving. Outputs using both models are evaluated in the following.

9.3.1 Case A analysis at level 3

Cost functions 1 and 2 as presented in subcases A.1 and A.2 respectively, are addressed in this section. The effect of cost functions could potentially differ based on the routing policy applied, so they are tested for each sublevel. Case situations are named as explained in the case description. As an example, a situation with a multi-element including time of lateness cost function with no-shows and emergency orders is named A.2 (25,50,∞).

Outputs using both cost functions in sublevel 3.1 are presented in Table 9-28, where additional output considering costs is presented in Appendix G. The subcases are compared in the bottom row, using subcase A.1 as benchmark. Costs are not given here, as there is no relationship between the actual numbers used in the cost generation for the two subcases considering order lateness. Costs are merely given as a penalty for delays, and minimising the costs in the objective function implies minimising delays. In addition, travelling costs and express costs are not present, as the distances travelled and express vessels conducted measure the same effect.

Case situation	Express 1500	3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance
A.1 (25,50,∞)	0	0	0	2.52	33 752	909 833	294 553
A.2 (25,50,∞)	1	0	25	2.22	29 652	819 060	291 999
A.2 vs. A.1 savings	*(1)*	*0*	*(25)*		*12.15 %*	*9.98 %*	*0.87 %*

Table 9-28: *Comparing level 3.1 subcases A.1 and A.2*

As one can see from the reductions presented, some saving in orders delay is present. Savings are however not as severe as they seem, as the numbers in the benchmark used are already small. On the contrary, cost function 1 serves no orders with express, as the scheduled vessels are able to serve all emergency orders within 8 departures. With the use of cost function 2 however, one express 1500 is conducted, serving 25 square meter demand at the additional express cost of $ 350 000. But as a saving in the distances travelled is evident as well, causing additional savings, it seems like a reasonable choice to proceed with cost function 2.

As mentioned, the effect of different cost functions may change when evaluating the situation where two visits to the same platforms is allowed, When decision makers are given the option to serve pickups and deliveries separately, additional solution shapes are evaluated as explained in Chapter 6. The optimal results considering service procedures and distances are based on the cost function in use, where the second visit option is weighted against possible reductions in order delay. The output produced when implementing both cost functions with a level 3.2 routing policy applied is given in Table 9-29.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance
A.1 (25,50,∞)	0	0	0	2.73	36 469	982 657	343 578
A.2 (25,50,∞)	4	0	112	2.47	33 030	911 118	339 328
A.2 vs. A.1 savings	*(4)*	*0*	*(112)*		*9.43 %*	*7.28 %*	*1.24 %*

Table 9-29: *Comparing level 3.2 subcases A.1 and A.2*

With a first glance on the comparison between the two cost functions, which can be found in the bottom row in Table 9-29, there seem to be a trade-off between express use and demand services. Some reductions are present when weighing more on actual order service as in cost function 2. However, this comes at the cost of leasing 4 express 1500. As for the output produces at level 3.1, distances travelled are reduced with the use of a cost function that weights more on minimising order inconvenience rather than minimising this. In addition, orders delayed for the longest are delayed for 29 and 11 departures with cost functions 1 and 2 applied, respectively. The findings are similar with the two routing policies applied, where order service seems to be most effective with cost function 2 implemented. Hence cost function 1 will be disregarded throughout this case study, whilst cost function 2 will be implemented when running the models for different case situation of case B.

9.3.2 Case B analysis at Level 3

Case B is divided into two subcases differing in how the no-show and emergency fractions are varied. In the first subcase B.1 the factual orders service situation at Petrobras using 25 % no-shows and 50 % emergency orders is simulated. Showing consistency with previous studies, subcase B.1 has been tested with three different overbooking percentages of 5, 10 and 25 %. In subcase B.2, no-shows only cover 15 % of orders, where the objective is to evaluate the further effect of dynamic routes if other parts of the supply chain are improved. In addition, a reduction in the number of emergency orders to 10 % is tested in both subcases. All output are given in Appendix G.

The variations within each subcase differ based on the overbooking percentages. The subcases are named as previously defined in the case description, so a situation with 25 % no-shows, 10 %

emergency orders and 20 % overbooking is referred to as B.1 (25,10,20). The costs are updated and calculated according to the cost function in subcase A.2.

B.1 Dynamic route generation in the factual order supply situation

As mentioned, the most important study here is to evaluate the influence of generating routes dynamically considering each departure as a separate optimisation problem. Table 9-30 presents the output produced with such a routing policy applied, where platforms are allowed one visit serving possible pickups and deliveries simultaneously (level 3.1). The bottom row in the same table compares the output produced with the same situation using fixed routes, namely the present situation. The total number of no-shows generated is around 2 105, which corresponds to 25 % of the delivery orders.

Case situation	Express 1500	3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance
B.1 (25,50,0)	1	0	25	2.22	29 652	819 060	291 999
Reductions from level 1	*519*	*0*	*99.92 %*	*66.15 %*	*66.15 %*	*70.08 %*	*16.00 %*

Table 9-30: *Level 3.1 subcase B.1 output*

Immense reductions concerning all measures are present, where large benefits using dynamic route generation are clearly evident. Only one express is conducted within the duration of a year in total, and orders now wait for 2.22 departures on average. As the complete output is Appendix G shows, orders are delayed for 13 departures at the longest. In addition, summing the number of orders that have to wait for more than the emergency limit, only 18 orders exceed 8 departures in delay. Based on this, the incentive to label orders as emergencies disappears. Hence, it could potentially be valuable to consider the same situation where instead the number of emergencies is set to 10 % of orders. 10 % emergencies correspond to a “normal” state at Petrobras, and is the actual expected number of emergencies according to statistics. This was implemented, and the corresponding output produced is given and compared to the present situation in Table 9-31.

Case situation	Express 1500	3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance
B.1 (25,10,0)	0	0	0	2.37	31 625	854 967	296 486
Reductions from level 1	*520*	*0*	*100 %*	*63.89 %*	*63.89 %*	*68.77 %*	*14.71 %*

Table 9-31: *Level 3.1 subcase B.1 output with 10 % emergencies*

Evaluating the output produced in Table 9-31 against the same output using 50 % emergencies in Table 9-31, order delay faces fewer reductions compared to the present situation. The upside however, is the reduction in express use. No orders are in this case served with express. In addition, at most one order has to wait for 12 departures before being served, which implies that all orders wait for less than a week.

Overbooking proved to be a valuable policy in the present situation, and should be investigates her as well. The effect is however expected to be less due to the already minor delays. Hence, the use of smaller overbooking percentages like 5 % and 10 % are tested. But an overbooking percentage equalling the no-show fraction is included, to demonstrate the effect. Table 9-32 presents the output produced using the proposed overbooking strategies. An emergency fraction of 50 % is used in the testing, as a reduction to 10 % emergencies is an uncertain effect of the applied routing policy.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance	Capacity exceeded
B.1-620 (25,50,5)	5	0	104	2.21	29 561	812 825	290 561	47
B.1-620 (25,50,10)	4	0	171	2.15	28 739	790 727	288 633	140
B.1-620 (25,50,25)	13	0	1 417	2.13	28 493	781 618	291 357	1 387

Table 9-32: Level 3.1 *Subcase B.1 model output*

As can be seen by the output in Table 9-39, planning with overbooking provokes express departures. The excess express usage, which comes in addition to the single express departure present in the situation with no overbooking, is strictly due to the demand still exceeding capacity when no-shows become known. Table 9-33 gives a summary of comparison made between the case situations, where reductions are given for changes from the benchmark of no overbooking to 5, 10 and 25 %, respectively.

Reductions compared to level 3.1 B.1 (25,50,0)

Case situation	Express demand	Delay in departures	Delayed demands	Travel distance
B.1 (25,50,5)	99.68 %	66.25 %	70.31 %	16.41 %
B.1 (25,50,10)	99.47 %	67.19 %	71.12 %	16.96 %
B.1 (25,50,25)	95.61 %	67.47 %	71.45 %	16.18 %

Table 9-33: *Comparing level 3.1 subcase B.1 with different overbooking percentages*

The upside of applying overbooking is shown in reductions considering order delay, where some additional reduction are present compared to the situation with no overbooking as presented in Table 9-30. These amounts are small as the benchmark is set low initially. In addition, some supplementary reductions are found in total travel distance. These reductions are however overshadowed by the costs that follow additional express leasing. Summarising these finding, it is evident that it is not especially effective to include any overbooking policy at all. With an average waiting time of 2.22 departures with no overbooking strategy, one could potentially assume that all participants will be satisfied. Considering orders delay, the biggest improvement with overbooking applied is present when 25 % overbooking is used. Nonetheless, it is assumed that the additional leasing of 12 express vessels is not made up for by the fact that orders are served within 2.13 departures rather than 2.22 departures on average.

However, if a vessel is allowed second visits to the same platform during voyage, the outcome may change. The output using a level 3.2 routing policy is presented in Table 9-34, where emergency percentages of 50 % and 10 % are simulated.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance
B.1 (25,50,0)	4	0	112	2.47	33 030	911 118	339 328
B.1 (25,10,0)	0	0	0	2.59	34 635	937 088	345 782

Table 9-34: Level 3.2 *Subcase B.1 model output*

Comparing the output produces with the same situation using a level 3.1 routing policy, as presented in Table 9-30 and Table 9-31 with emergency fractions of 50 % and 10 % respectively, additional express leasing is present in the situation with 50 % emergencies. Reductions in important measures are calculated in Table 9-35, where the level 3.1 output serves as benchmark.

Reductions from level 3.1 B.1 (25,θ,0) to level 3.2 B.1 (25,θ,0)

Emergency θ	Express demand	Delay in departures	Delayed demands	Travel distance
50 %	(348 %)	(11.39 %)	(11.24 %)	(16.21 %)
10 %	0 %	(9.52 %)	(9.61 %)	(16.63 %)

Table 9-35: *Comparing subcase B.1 at levels 3.1 and 3.2*

By looking at the comparison presented, all parameters are in fact increasing when the option to visit platforms twice is added. This is surprising given that level 3.2 incorporates all the same possibilities as in level 3.1, and is less restricted voyage-wise. Quite the opposite is anticipated, as mentioned in Chapter 6. One would expect the output using a level 3.2 routing policy to be at least as good as when level 3.1 is applied, as previously illustrated in Figure 6-5. Nevertheless, the differences are not significant given the already low benchmark in order delay and express. Increased travel distance however, is anticipated, where two visits to the same platforms induce more sailing. There may be several reasons for the unexpected outcome. Some proposed reasons to why are summarised below, followed by a short discussion for each.

(1) *Presence of close to optimal solutions*
(2) *Departure-optimality is not necessarily equal to total year-optimality*
(3) *Inconsistency in measures and model objectives*

Firstly of, proposal (1) is considered. In the introduction of this section it was mentioned that an upper solution time was set in a way of coping with the complex nature of model level 3.2. The simulations presented using a level 3.2 routing policy are restricted by a solution time of 15 minutes, where some of the data produced are only close-to-optimal estimates. For the level 3.1 model runs however, optimal result for all iterations are present as no limit restricted total solution time. This implies that comparison in Table 9-35 relates estimated results to optimal results, which is somewhat unfair in representation.

Secondly, proposal (2) points out an important fact when simulation for optimisation is used: what is optimal for one-iteration alone is not necessarily optimal when simulating for a year in total. Each iteration in this case represents a given departure. All decisions made in one-departure affects the succeeding, where they trigger a chain of events. As an example, it may seem reasonable to let a given order stay unserved in one departure, assuming its service on the next. However, orders present in the next departure are unknown to the decision maker, as new order are requested at each departure. This may induce unforeseen order delays, which is outside the planning horizon when decisions are made. If this failing outcome where more present in the level 3.2 than the 3.1 simulation, it could possibly explain some of the differences. Still, as the level 3.2 model was run for several situations, all showing a pretty consistent pattern when compared to same situations at level 3.1, this alone can not be the factor causing unexpected results.

The last proposal mentioned however, is provable. By evaluating the actual objective values generated for a year in total, the comparison between level 3.1 and 3.2 shows something else. Table 9-36 illustrates a comparison between objective values produced at levels 3.1 and 3.2, using the factual order supply situation with 25 % no-shows and 50 % emergencies.

Case situation	Total year cost	Total year order lateness cost	Total year sailing cost
Level 3.1 B.1 (25,50,0)	$ 9 726 million	9 584 million	$ 123 million
Level 3.2 B.1 (25,50,0)	$ 9 265 million	$ 9 123 million	$ 143 million
Level 3.2 vs. 3.1 savings	*4.73 %*	*4.81 %*	*(16.21 %)*

Table 9-36: *Level 3 objective values*

Two cost functions are included in the objective function: order lateness cost, which sums the inconvenience cost coupled to each order, and sailing cost. The actual number used considering the cost of sailing belongs to the group of direct costs, meaning it is factual and given. The order lateness however, is based on the author's subjective opinion. By looking at the comparison between the total objective values generated with level 3.1 and 3.2 in use, it is evident that the simulation solution is better in the latter, where total year costs is reduced by 4.73 %. This reduction steams from a reduction in total year order lateness cost of 4.81%. The measures previously compared in Table 9-35 however, show the opposite. This implies that the objective functions of the models implemented do not seem to reflect the measure objectives discussed to the same extent, which is to reduce actual order lateness as much as possible while saving costs. Adjustments in the cost function used could potentially affect the outcome.

Nevertheless, simulation with both models of level 3 in use showed large potentials, and it is evident by looking at differences in the objective values presented that there in some situations exists an incentive to serve the same platforms twice. However, based on the numbers generated, model level 3.1 simulated the best outcome, and this will be evaluated in the following. By looking at the data presented in Table 9-30 and Table 9-31, large reductions are apparent when comparing the situations with the factual. All orders could potentially be served within a week, where orders wait for 2.22 or 2.13 departures on average, depending on the emergency fraction. In addition, express is nearly never issued, which corresponds to severe savings cost-wise.

What is unanswered though, are the reasons to why fixed routes are in use when dynamic routes are clearly more beneficial considering the measure discussed. As earlier mentioned, fixed routes were settled to make order service more predictable. What the analysis presented in Section 9.1 illuminated is that 50 % of orders are requested as emergencies, whilst in fact the fraction should be 10 %. Considering this, the fixed routes in use do not seem to serve their purpose, and the lack of trust still exists. Even if issues outside the scope of this study prevent the use of dynamic route generating as of today, knowing the benefits could act as an incentive to make an effort in the case.

B.2 Reduction of no-shows in addition to flexible routes

Implementing dynamic routes to the factual supply order problem with 25 % no-shows established that there exists numerous advantages considering orders delays, cost saving, travel distance and express use. Evaluating this further, the next step would be to assess the effect of onshore logistics managing problems on other parts of the supply chain. The data output for level 3 using a no-show fraction of 15 %, regarding both 50 % and 10 % emergencies is presented in Table 9-37.

Case situation	Express 1500	Express 3000	Express demand	Waiting time	Delay in departures	Delayed demands	Travel distance
Level 3.1 B.2 (15,50,0)	0	0	0	1.77	23 642	643 932	291 767
Level 3.2 B.2 (15,50,0)	0	0	0	1.82	24 459	657 492	343 615
Level 3.1 B.2 (15,10,0)	0	0	0	1.81	24 268	643 216	290 360
Level 3.2 B.2 (15,10,0)	0	0	0	1.84	24 707	646 500	346 475

Table 9-37: Level 3 *subcase B.2 model output*

Express vessels are never issued with 15 % no-shows present. In addition, orders now wait between 1.77-1.84 departures on average for service, depending on the dynamic routing policy and the number of emergencies present. The output presented in Table 9-37 is further compared to the factual situation using fixed routes, and 25 % and 50 % no-shows and emergencies respectively, in Table 9-38.

Reductions from level 1 B.1 (25,50,0) (present situation)

Case situation	Express demand	Delay in departures	Delayed demands	Travel distance
Level 3.1 B.2 (15,50,0)	100.00 %	73.01 %	76.48 %	16.06 %
Level 3.2 B.2 (15,50,0)	100.00 %	72.07 %	75.98 %	1.15 %
Level 3.1 B.2 (15,10,0)	100.00 %	72.29 %	76.51 %	16.47 %
Level 3.2 B.2 (15,10,0)	100.00 %	71.79 %	76.39 %	0.32 %

Table 9-38: *Comparing level 3 subcase B.2 with the present situation*

As expected, order delay is reduced further when no-shows only apply for 15 % of the planned order service. However the effect is immense compared to the same comparisons in the level 1 and level 2 analyses, which illuminates the severe effect that no-shows actually have in the order service setting. In addition, one would expect that by reducing the emergency fraction as well, as presented in the lower rows of Table 9-38, more gain would come from effective planning when less attention is given to emergency service and more is put on actual order size and vessel utilisation. This seems to be evident to some distinct, as demand delayed is reduced further when the emergency fraction is reduced. In addition, as the distances travelled are less with 10 % emergencies present, supplementary attention is now given to the actual routes conducted. No lateness cost of great significance is present when most orders are served within two departures, freeing objective space for additional voyage planning in the optimization.

Chapter 10

Concluding remarks

The purpose of this paper has been to develop a general tool for logistics planning that can be useful in practice, and to make use of this to examine different planning and routing strategies addressing the current challenges in Petrobras' supply chain. The study is a standalone paper, which has culminated in both valuable findings and recommendations for decision makers as well as a basis for future work and research on similar topics.

The author has spent time learning about the logistics system at Petrobras and identified challenges present in the supply chain. This was accompanied by a closer look at the interplay between different supply chain elements, more specifically the cycle where supply order requests are sent from facilities offshore to the logistics central onshore and planning problems are solved concerning the orders to be served. The cycle concludes with the arrival of orders at the port and loading on board the platform supply vessels scheduled for the departure. This routine is influenced by various components, both human and technical. The routes and schedules at Petrobras are currently fixed, a strategy implemented as a response to distrust between supply chain participants to ensure predictability and avoid an unnecessary high number of complaints and urgent requests from facilities. Based on this, the analysis was initiated by retaining this strategy using the actual routes and schedules present at Petrobras. This served as a periodic planning tool, solving the problem for one departure at a time with a given set of orders and a route policy applied. The benefits from the model arise when simulation is included in the program, and the model was run for a year in total to imitate the actual situation with dynamic generation of orders.

Different models were formulated, incorporating a supply order problem with different proposed alternatives to the current fixed routes in use. The first model however, imitated the present situation, where the main aim was to construct a model that provided the best problem solutions using the currently fixed routes and also represented reality. Considering this, the intention was to uncover the underlying issues as of today. This was achieved by introducing some changeable parameters with one being the cost functions, meaning the penalising policy for delay in serving orders. The delay was minimised through a minimisation of the delay costs, which were based on the size of orders, in addition to the orders being pickups or deliveries.

Petrobras currently experience problems in their supply chain originating in onshore logistics, where 25 % of the orders scheduled for a given departure arrive at the port too late to be transported. No-shows lead to low utilisation of the vessels, which is followed by increased waiting times for orders to be served and large quantities of demand delayed. Platform operators seem to cope with this fact by requesting emergencies in the place of normal orders. 50 % of orders are currently requested as emergencies, where according to statistics the numbers should in fact be 10. Following this, express vessels are conducted on a frequent basis, serving all emergencies reaching their delay limit. This is a very costly operation.

Overbooking is a strategy that can potentially correct parts of the problem. This was proven when planning for 20-25 % excess capacity than the actual, where the expected delays were reduced by one third. There is however a trade-off due to the uncertain nature of the problem. For departures where there are less no-shows than expected, one might end up scheduling more demand than the vessel can take, so the deck capacity would be exceeded. An express departure would have to be arranged to deliver the excess demand, and this represents the downside of the policy. Even so, as numerous express departures are already conducted due to the hefty amount of emergencies, excess express demand does not necessarily result in additional express leasing. On the contrary, a better utilisation of the already present express departures seems to be evident.

The next strategy applied challenged the fixed routes currently in use. Flexibility was added with the option to exclude platforms from a given route. There is a trade-off here, where savings in sailing is followed by additional express demand. However, in most cases it is apparent that the effect of savings made ultimately covers additional express use. As more orders are served with express, reductions in order delay follow. Even though the simulation for a year in total showed interesting prospects, it could potentially be difficult for decision makers to make due with such a policy. It requires trust among all participants to be effective, which seems to be lacking in the presence.

A proposed route policy showing clear advantages to the fixed currently in use, is dynamic route generation. Reductions by more than 70-75 % are apparent, while express voyages are nearly non-existing. However, considering the factual state it seems evident that Logistics are not compatible with dynamic route planning as of today. They are facing internal uncertainties in the supply chain and have implemented fixed PSV route and schedules to create reliability in order handling. Nonetheless, as the study presented illustrates, the issue still seems to exist considering the amount of no-shows and emergencies present. Fronting a further tactical approach to planning may be necessary to gain trust among stakeholders. And with this re-established, as well transparency along the supply chain, it is the author's belief that such an operational model could be the next step towards further improvements.

In addition, when considering all of the routing policies applied, it seems reasonable to assume that great savings can be achieved from reductions in the share of no-shows especially. No analysis is of course needed to state the fact that no-shows should ideally be non-existing. Still, it is useful to quantify the impacts to clearly show the potential. Improvements in the relevant parts of the supply chain may be both costly and require internal changes, but knowing the benefits could act as an incentive to make an effort in the case. It is also a foundation for further studies where research can be focused on the onshore transportation and communication system, to identify the failures leading to no-shows and coming up with ways of correcting these.

Chapter 11

Future research

In this paper, a general tool and approach to logistics planning have been developed. The model has been implemented and applied to relevant issues for Petrobras. In this chapter some potential areas that could be investigated in future research will be explained briefly.

First, the current model can be expanded and modified to improve its imitation of the actual situation for Petrobras. More data can be obtained to make the simulation better, such as more details around the routes, capacities on vessels, typical orders and platform characteristics. Especially knowing the actual facility coordinates could benefit the analyses, as these are just estimates in the present study, and are sensitive with regards to implementation faults. In addition, only the capacity of a PSV 3000 is used. It it a know fact that PSV 4500 is currently being scheduled for as well, although not as frequent as PSV 3000. Optimizing the actual fleet mix could serve as an advantage. Considering vessel capacity further, the problem could for instance include the feasibility of orders on the vessels by considering the shape of the orders and possible ways to allocate them on deck. With fixed routes and schedules, priority would not be given to time constraints or vessel performance, but rather to a true representation of the order cycle. If incorporating dynamic routes however, the actual time and frequency of departures could potentially be investigated.

Expansions of the model could furthermore be done to change the focus of the problem to either offshore or onshore logistics. This study has proven that great savings can be achieved from reductions in the share of no-show orders. This can be addressed from an onshore logistics point of view, where the objective would be to find different ways of improving both the truck transportation from warehouses to the port and the communication systems in use by supply chain members. Overbooking is an interesting policy that may be worthwhile to include in any of proposed routing policies. It is also possible to develop this strategy and research its potential and limitations for the present setting, as the study in writing not necessarily has the same outcome when implemented in practice. The trade-off between higher ship utilisation and costs for express departures needs to be studied more in depth. Real costs for additional vessels can be found, but a higher degree of difficulty is related to determining appropriate measures for the inconvenience costs of delayed orders. This latter point is highly relevant for the models in general, and company or industry representatives may be able to give a better understanding of the importance of different orders.

A natural progression in the offshore transportation area is to challenge the fixed routes and schedules that are currently in use and examine if the chosen sets are optimal. Dynamics in routes and schedules proved to have a positive impact, but one has to take the issues of trust for the supply chain into account as well, considering the history of Petrobras. With dynamic planning many factors come into play, such as ship abilities, uncertainty arising from for example unstable weather conditions, and restrictions on time and service. Also the actual number of departures in use, in the time they are scheduled could potentially be challenged. The use of dynamic route planning could be of great value for more efficient vessel fleet, especially in relation to the Petrobras 2020 vision and future exploitation and search in the pre-salt areas in Santos basin.

Finally, since the models with changeable parameters are not specific to Petrobras necessarily, they can be developed and applied to different problems to test its robustness and further enhance its usefulness. Emphasis can be put on the simulation part of the approach, to allow decision makers to test long-term decisions in a realistic environment.

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Appendix A

Platforms and Schedules

Figure A-1 shows a departure schedule for platform supply vessels in Petrobras, which is related to convenience goods. Each row represents a weekday, starting on Monday and ending on Sunday. Six of the days have two departures given as two separate rows, except for Sunday, which has one departure. Each departure is represented by platforms visited, which corresponds to a route given in the sequence order of visitation for platforms. The parameter Q represents the number of platforms in each route, and the time of departure is given in the rightmost column.

BR PETROBRAS ROTINA PARA PROGRAMAÇÃO

E&P-SERV / US-LOG / LOGM / TM

TABELA DE CARGA / RANCHO / ÁGUA : UNIDADES DE PRODUÇÃO

DIA SAÍDA	UNIDADES MARÍTIMAS										Q	EMBARCAÇÕES	HORÁRIO DE SAÍDA
SEGUNDA	FPMS	P-26	P-35	P-37	P-38	P-40					6	PSV 3000 / 4500	24:00
	FPRO	P-07	P-12	P-15	PCE1	PPM1	P-65				7	PSV 3000 / 4500	12:00 ([illegible])
TERÇA	P-18	P-19	P-20	P-27	P-32	P-33	P-47	P-53	UMQS		9	PSV 3000 / 4500	24:00
	PCH1	PCH2	PGP1	PNA1	PNA2	PPG1	UMCA				7	PSV 3000 / 4500	12:00 ([illegible])
QUARTA	FPBR	FSME	P-25	P-31	P-50	P-52	P-54	PRA-1	CIAC		9	PSV 3000 / 4500	24:00
	FPNT	FPRJ	P-08	P-09	P-43	P-48	P-51	P-56			8	PSV 3000 / 4500	12:00 ([illegible])
QUINTA	FPRO	P-07	P-12	P-15	P-65	PCE1	PPM1				7	PSV 3000 / 4500	24:00
	FPMS	P-26	P-35	P-37	P-38	P-40					6	PSV 3000 / 4500	12:00 ([illegible])
SEXTA	PCH1	PCH2	PGP1	PNA1	PNA2	PPG1	UMCA				7	PSV 3000 / 4500	24:00
	P-18	P-19	P-20	P-27	P-32	P-33	P-47	P-53	UMQS		9	PSV 3000 / 4500	12:00 ([illegible])
SÁBADO	FPNT	FPRJ	P-08	P-09	P-43	P-48	P-51	P-56			8	PSV 3000 / 4500	24:00
	FPBR	P-25	P-31	P-50	P-52	P-54	CIAC				7	PSV 3000 / 4500	12:00 ([illegible])
DOMINGO	FSME	PCP1	PCP2	PCP3	PRA-1	PVM1	PVM2	PVM3			8	PSV 3000 / 4500	24:00
ATT:	1) FORNECER ÁGUA, CARGA E RANCHO SOMENTE PARA AS UM'S DO CRONOGRAMA.												
	2) FAZER BACK LOAD SOMENTE PARA AS UM'S DO CRONOGRAMA.												
	3) MANTER A PROGRAMAÇÃO PARA OS GRUPOS DESCRITOS ACIMA, ALTERANDO SOMENTE O ROTEIRO CONFORME A NECESSIDADE.												

Figure A-1: *Departure schedule of order service currently operated by Petrobras*

To simplify the routes and their corresponding platforms, each platform is given a number from 1 to 52. The port at Macaé is given the number 0. This can be seen in Table A-1, in addition to other information coupled to facilities like facility type (production/drilling) and coordinates.

Platform number	Platform name	Production/ Drilling	Coordinates x [km]	y [km]	Platform number	Platform name	Production/ Drilling	Coordinates x [km]	y [km]
0	Macaé	Prod	10	59	**27**	P-27	Prod	183	74
1	FPMS	Prod	203	38	**28**	FPNT	Prod	179	88
2	FPRO	Prod	223	127	**29**	FPRJ	Prod	196	59
3	PCE1	Prod	170	75	**30**	P-50	Drill	213	114
4	PPM1	Prod	149	70	**31**	P-31	Prod	199	110
5	UMQS	Prod	184	79	**32**	P-32	Prod	164	70
6	PGP1	Prod	197	73	**33**	P-33	Prod	189	74
7	P-7	Prod	125	16	**34**	P-51	Drill	188	32
8	P-8	Prod	138	24	**35**	P-35	Prod	184	64
9	P-9	Prod	141	38	**36**	P-52	Drill	222	131
10	PCH1	Prod	141	61	**37**	P-37	Prod	179	54
11	PCH2	Prod	162	63	**38**	P-38	Prod	183	44
12	P-12	Prod	113	16	**39**	P-53	Drill	210	47
13	PNA1	Drill	162	66	**40**	P-40	Drill	189	41
14	PNA2	Drill	163	65	**41**	P-54	Drill	213	125
15	P-15	Prod	133	23	**42**	P-56	Drill	197	33
16	PPG1	Prod	176	87	**43**	P-43	Drill	161	52
17	UMCA	Prod	173	88	**44**	P-47	Drill	172	60
18	P-18	Prod	193	69	**45**	P-48	Drill	158	31
19	P-19	Prod	191	72	**46**	P-65	Prod	142	76
20	P-20	Prod	188	75	**47**	PCP1	Prod	144	90
21	FPBR	Prod	157	49	**48**	PCP2	Prod	149	92
22	FSME	Prod	140	90	**49**	PCP3	Prod	145	88
23	PRA-1	Prod	198	117	**50**	PVM1	Prod	164	103
24	CIAC	Prod	8	27	**51**	PVM2	Prod	162	99
25	P-25	Prod	203	108	**52**	PVM3	Prod	161	97
26	P-26	Prod	193	66					

Table A-1: *Facilities*

Appendix B

Input data calculations

This appendix provides some supplementary information and calculation considering the input data explained in Chapter 8. In Section B.1 the distance matrix calculations are explained, where a description considering the procedure of gathering facility coordinates is given. The three latter sections illustrate how the delay limit for emergency orders, voyage duration of the fixed routes currently in use, and indirect costs coupled to pickups and deliveries are calculated, respectively. All in all, this appendix is an addition to section 8.1 in Chapter 8.

B.1 Distance matrices

The distance matrices are base on facility coordinates. The present platform coordinates are valued as confidential information and can correspondingly not be obtained from Petrobras. Some creative methods were applied to gather the coordinates. However, the coordinates of 19 platforms, including the port in Macaé were found in Vidaer and Uglane (2013). Coordinates of the remaining 33 platforms were found by the use of different maps, drawing the coordinates already given in addition to creating different proportional numbers and measures while approaching different approximates for the remaining platforms. For a small collection of platforms however, only loose ideas of the areas in which they are installed could be obtained. Hence, the coordinates used and presented in this thesis are not 100 % accurate. Nevertheless they all seem to correspond as good estimates taking the travel duration into account when looking at the fixed routes currently in use. A complete map showing approximates considering facility placements is given in Figure 7-1. All coordinates, both the ones calculated and given are presented in Table B-1. In addition, a collection of the maps used when calculating the missing platform coordinates are presented in Figure B-1 – Figure B-3.

With all facility coordinates settled, the distance matrices could easily be calculated. The following formula is used in the distance calculations:

$$D_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

Here x and y serves at the coordinates for platforms i and j, while D_{ij} is the calculated distance between them. The complete matrices, using both a single-node- and two-node-formulation depending on the level, can be found in an excel file in Appendix D.

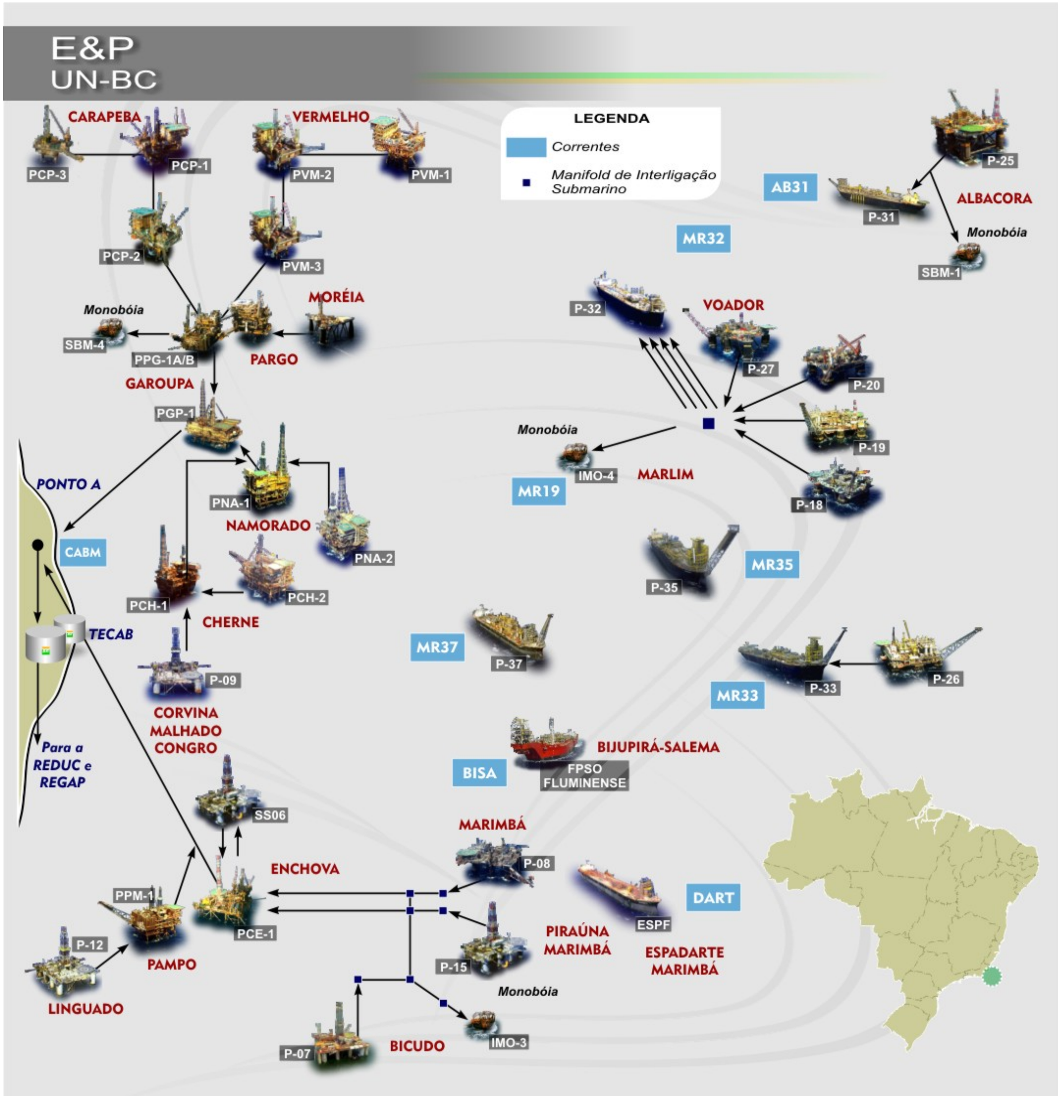

Figure B-1: *Map 1 of Campos basin (Click Macaé, 2014)*

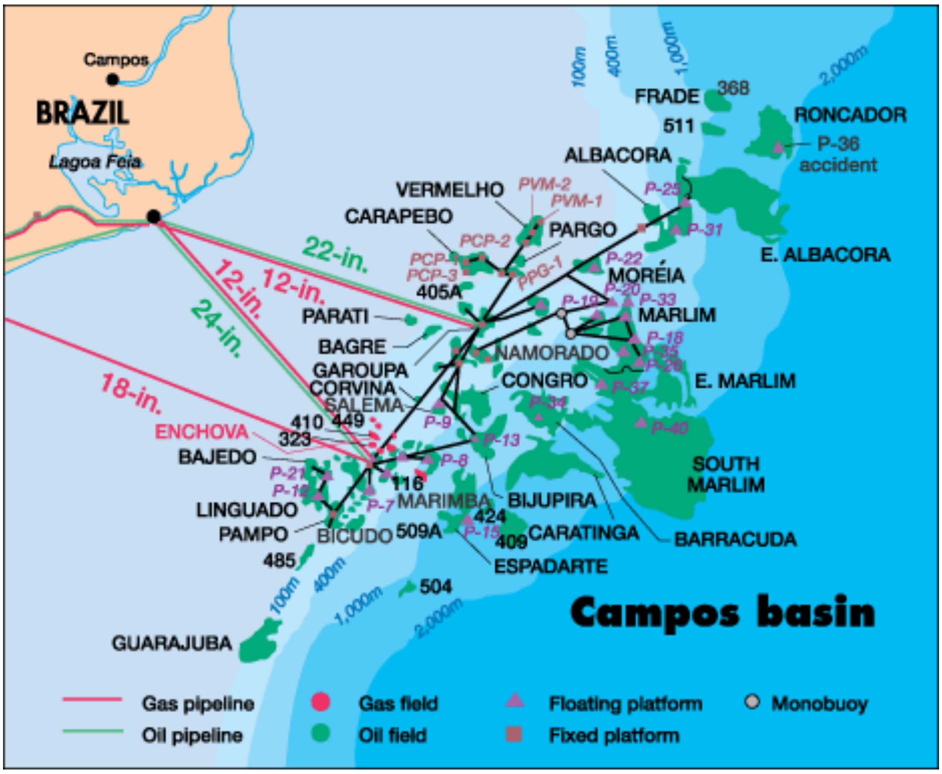

Figure B-2: *Map 2 of Campos basin (International Oil & Gas News, 2013)*

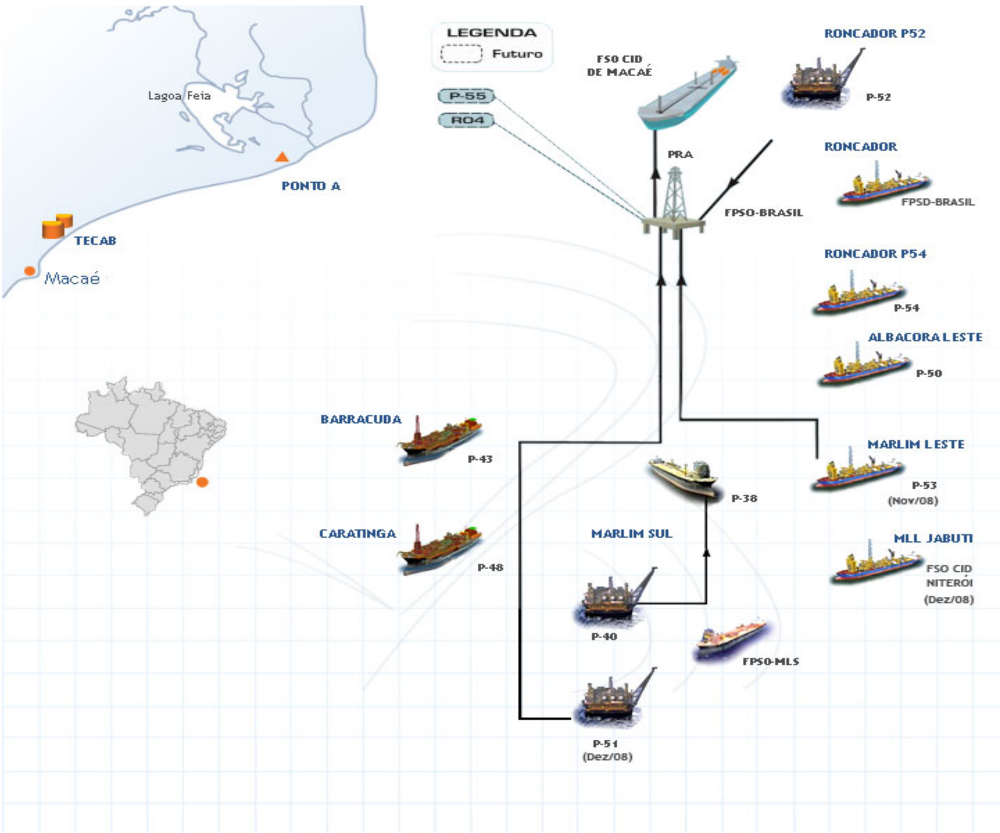

Figure B-3: *Map 3 of Campos basin (Petrobras, 2013)*

B.2 Emergency order delay limit

A delay limit for emergency orders it settled in this section. The term emergency is used when the platforms require the cargo to be delivered earlier than 10 days after the transfer requests (RT) is recorded in SAP. Friedberg and Uglane (2013a) present an overview of the different stages considering order handling and the corresponding time consume in the logistics section at Petrobras. A simple calculation using this information is performed in Table B-1, where the delay limit corresponding to 10 days in departures is calculated.

	Time consume
Delay limit (10 days)	+ 240 hours
Pre-programming, send requisition list to warehouse	- 8 hours
Review of list. Re-programming if items are missing in warehouse	- 2 hours
Make code for SAP. Almost finalised cargo list	- 8 hours
Finalised cargo list	- 12 hours
Deadline for arrival at port. Started offloading of vessel	- 6 hours
Finished offloading. Deadline to begin loading of vessel	- 6 hours
Loading should be finished. Departure deadline	- 6 hours
Maximum duration of a voyage, including platform on-/offloading	- 72 hours
Off-loading to port on arrival	- 6 hours
Delay limit [Hours]:	+ 114 hours
Delay limit [Departures]:	+ 8.82 departures

Table B-1: Emergency order delay limit calculation

The following formula is used in Table B-1 when transforming the delay limit from hours to departures:

$$Delay\ limit\ [Departures] = \frac{13\ [\frac{Departures}{week}]}{168\ [\frac{Hours}{week}]} \cdot Delay\ limt\ [Hours]$$

As one can see from the calculation made in Table 7-1, emergency orders have to be served within 8.82 departures. Hence, the corresponding delay limit is set to 8 departures.

B.3 Voyage duration

When routes are made dynamic in model level 3, voyage duration is settled. Table B-2 shows the duration limit of the current routes in use, where the aim is to see whether all routes conducted are within the time limit of 3.5 days. Loading operation on port may take a total of 12 hours, which includes both the loading of vessels prior to departure, and off-loading when the vessels arrives back at port. The calculations for the currently used fixed and predetermined routes all are within the limit of 3.5 days. Subtracting the depot load duration of 12 hours from the total duration puts the total voyage limit to 72 hours.

Route	Platforms visited	Sailing [Km]	Sailing [Hours]	Platform loading [Hours]	Depot loading [Hours]	Total [Hours]	Total [Days]
1	6	442	24	24	12	60	**2.5**
2	7	633	34	28	12	74	**3.1**
3	9	518	28	36	12	76	**3.2**
4	7	420	23	28	12	63	**2.6**
5	9	565	31	36	12	79	**3.3**
6	8	560	30	32	12	74	**3.1**
7	7	648	35	28	12	75	**3.1**
8	6	442	24	24	12	60	**2.5**
9	7	420	23	28	12	63	**2.6**
10	9	518	28	36	12	76	**3.2**
11	8	560	30	32	12	74	**3.1**
12	7	530	29	28	12	69	**2.9**
13	8	408	22	32	12	66	**2.8**
Average	**8**	**513**	**28**	**30**	**12**	**70**	**2.9**

Table B-2: *Fixed route duration*

B.4 Indirect costs

This section describes the procedure performed when calculating the proposed costs per demand delayed for both pickups and deliveries. Table B-3 below shows the calculation conducted, where proposed costs per demand delayed for both pickup and delivery are proposed as \$ 400 and \$ 800, respectively.

The possible order delay cost of a departure should be both more than the scheduled vessel cost and less than express. With the use of a PSV 3000, the cost when including both fixed and variable sums up to \$ 337 960. This is calculated by using the average travel distance of 513 kilometres for the fixed route currently in use, which is calculated in Table 7-2. Deliveries are more valued compared to pickups, so setting a double cost in comparison seems reasonable. Using the total demand requested in a year, as presented in the model outputs in Chapter 8, and dividing it by 678 departures (52 weeks), 389 and 154 delivery and pickup demand respectively, are requested on average for each departure. This puts the service price of all orders to be \$ 372 548, which is a reasonable amount considering the average of vessel and express costs set to \$ 378 980. With this calculation as a basis, deliveries and pickups are valued to \$ 800 and \$ 400 per square meter delay, per departure in this study.

	Demand m^2	Given costs \$	Calculated costs $\$/m^2$	Calculated costs \$
Scheduled vessel	< 620	\$ 337 960		\$ 378 980
Express	< 240/620	\$ 420 000		
Delivery demand	389		**\$ 800 $/m^2$**	\$ 311 200
Pickup demand	154		**\$ 400 $/m^2$**	\$ 61 600
Total order delay	543			\$ 372 960

Table B-3: *Indirect cost calculation*

Appendix C

The SOP formulation

Sets

P	$P = \{1, \dots, \bar{P}\}$	Set of all platforms ($\bar{P}$ platforms in total)
P^T	$P^T \subseteq P$	Subset of platforms in the given route
K	$K = \{0, \dots, \lvert P^T \rvert\}$	Set of sequence numbers coupled to facilities in the given route, where $p = p(k)$ for $k \in K$, and $\{0\}$ is coupled to the depot.
O_p	$p \in P$	Set of orders for platform p
${O_p}^D$	$p \in P, {O_p}^D \subseteq O_p$	Set of delivery orders for platform p
${O_p}^P$	$p \in P, {O_p}^P \subseteq O_p$	Set of pickup orders for platform p

Parameters

K		The vessel deck capacity in square meters
Q_o	$p \in P, o \in O_p$	Demand requirement for order o in square meters
${C_o}^L$	$p \in P, o \in O_p$	Lateness cost due to an order o not being served

Variables

u_o	$p \in P^T, o \in O_p$	1 if order o is served, 0 otherwise
l_p	$p \in P^T$	Load on board the vessel leaving platform p

Model

$$\min \sum_{p\in P^T} \sum_{o\in O_p} C_o{}^L \cdot (1-u_o) \tag{C.0}$$

s.t.

$$l_0 = \sum_{p\in P^T} \sum_{o\in O_p{}^D} Q_o u_o \tag{C.1}$$

$$l_{p(k)} = l_{p(k-1)} - \sum_{o\in O_{p(k)}{}^D} Q_o u_o + \sum_{o\in O_{p(k)}{}^P} Q_o u_o \qquad k \in K \tag{C.2}$$

$$0 \le l_p \le K \qquad p \in P^T, \{0\} \tag{C.3}$$

$$u_o \in \{0,1\} \qquad p \in P^T, o \in O_p \tag{C.4}$$

Appendix D

The SOP-FR formulation

Sets

P	$P = \{1, \dots, \bar{P}\}$	Set of all platforms ($\bar{P}$ platforms in total)
P^T	$P^T \subseteq P$	Subset of platforms in the given route
N	$N = \{0, \dots, \overline{P^T} + 1\}$	Set of nodes coupled to facilities in the given route, by $p = p(i)$ for $i \in N$. $\{0\}$ and $\{\overline{P^T} + 1\}$ represent the depot, where $\overline{P^T}$ is the number of platforms in the given route
N^F	$N^F = \{1, \dots, \overline{P^T}\} \subseteq N$	Set of nodes coupled to platforms by $p = p(i)$ for $i \in N$
N^L	$N^L = \{0, \dots, \overline{P^T}\} \subseteq N$	Set of leaving-nodes coupled to facilities, by $p = p(i)$ for $i \in N$
O_p	$p \in P$	Set of orders for platform p
${O_p}^D$	$p \in P, {O_p}^D \subseteq O_p$	Set of delivery orders for platform p
${O_p}^P$	$p \in P, {O_p}^P \subseteq O_p$	Set of pickup orders for platform p
A	$(i,j) \in A, i,j \in N, i < j$	Set of arcs, from node i to node j

Parameters

K		The vessel deck capacity in square meters
Q_o	$p \in P, o \in O_p$	Demand requirement for order o in square meters
${C_o}^L$	$p \in P, o \in O_p$	Lateness cost due to an order o not being served
C^S		Sailing cost per distance travelled
D_{ij}	$(i,j) \in A$	Sailing distance from node i to node j

Variables

u_o	$p \in P, o \in O_p$	1 if order o is served, 0 otherwise
l_i	$i \in N^L$	Load on board the vessel leaving node i
v_i	$i \in N^F$	1 if node i is served, 0 otherwise
x_{ij}	$(i,j) \in A$	1 if the vessel travels from node i to j, 0 otherwise

Model

$$minimize \quad \sum_{p \in P^T} \sum_{o \in O_p} C_o{}^L (1 - u_o) + \sum_{(i,j) \in A} C^S D_{ij} x_{ij} \tag{D.0}$$

s.t.

$$\sum_{j \in N} x_{0,j} = 1 \tag{D.1}$$

$$\sum_{i \in N} x_{i,\overline{P^T}+1} = 1 \tag{D.2}$$

$$\sum_{j \in N} x_{ij} = v_i \qquad i \in N^F \tag{D.3}$$

$$\sum_{i \in N} x_{ij} = v_j \qquad j \in N^F \tag{D.4}$$

$$v_i \geq u_o \qquad i \in N^F, o \in O_{p(i)} \tag{D.5}$$

$$l_0 = \sum_{i \in N^F} \sum_{o \in O_{p(i)}{}^D} Q_o u_o \tag{D.6}$$

$$0 \leq l_i \leq K \qquad i \in N^L \tag{D.7}$$

$$l_j \geq l_i - \sum_{o \in O_{p(j)}{}^D} Q_o u_o + \sum_{o \in O_{p(j)}{}^P} Q_o u_o - (1 - x_{ij})K \qquad i \in N^L, j \in N^F, i < j \tag{D.8}$$

$$x_{ij} \in \{0, 1\} \qquad (i,j) \in A \tag{D.9}$$

$$u_o = \{0, 1\} \qquad p \in P^T, o \in O_p \tag{D.10}$$

$$v_i = \{0, 1\} \qquad i \in N^F \tag{D.11}$$

Appendix E

The SOP-DR-1 formulation

Sets

V	$V = \{0, \dots, \bar{P} + 1\}$	Set of all nodes including the depot $\{0\}$ and $\{\bar{P} + 1\}$, where $\bar{P}$ is the number of platforms
V^F	$V^F = \{1, \dots, \bar{P}\} \subseteq V$	Set of nodes coupled to platforms (offshore facilities)
O_i	$i \in V^F$	Set of orders for node i
${O_i}^D$	$i \in V^F, {O_i}^D \subseteq O_i$	Set of delivery orders for node i
${O_i}^P$	$i \in V^F, {O_i}^P \subseteq O_i$	Set of pickup orders for node i
A^1	$(i,j) \in A^1, i,j \in V, i \neq j$	Set of arcs, from node i to node j

Parameters

K		The vessel deck capacity in square meters
Q_o	$i \in V^F, o \in O_i$	Demand requirement for order o in square meters
${C_o}^L$	$i \in V^F, o \in O_i$	Lateness cost due to an order o not being served
C^S		Sailing cost per distance travelled
D_{ij}	$(i,j) \in A^1$	Sailing distance from node i to node j
S		Operating speed
T^S		Service duration
T^L		Voyage duration limit

Variables

u_o	$i \in V^F, o \in O_i$	1 if order o is served, 0 otherwise
l_i	$i \in V$	Load on board the vessel leaving node i
v_i	$i \in V^F$	1 if node i is served, 0 otherwise
x_{ij}	$(i,j) \in A^1$	1 if the vessel travels from node i to j, 0 otherwise

Model

$$minimize \quad \sum_{i\in V^F}\sum_{o\in O_i} C_o{}^L(1-u_o) + \sum_{(i,j)\in A^1} C^S D_{ij}x_{ij} \tag{E.0}$$

s.t.

$$\sum_{j\in V} x_{0,j} = 1 \tag{E.1}$$

$$\sum_{i\in V} x_{i,\bar{P}+1} = 1 \tag{E.2}$$

$$\sum_{j\in V} x_{ij} = v_i \qquad i\in V^F \tag{E.3}$$

$$\sum_{i\in V} x_{ij} = v_j \qquad j\in V^F \tag{E.4}$$

$$v_i \geq u_o \qquad i\in V^F, o\in O_i \tag{E.5}$$

$$l_0 = \sum_{i\in V^F}\sum_{o\in O_i{}^D} Q_o u_o \tag{E.6}$$

$$0\leq l_i \leq K \qquad i\in V \tag{E.7}$$

$$l_j \geq l_i - \sum_{o\in O_j{}^D} Q_o u_o + \sum_{o\in O_j{}^P} Q_o u_o - (1-x_{ij})K \qquad (i,j)\in A^1 \tag{E.8}$$

$$\sum_{(i,j)\in S} x_{ij} \leq |S|-1 \qquad S\subset V^F, |S|\geq 2 \tag{E.9}$$

$$\frac{1}{S}\sum_{(i,j)\in A^1} D_{ij}x_{ij} + T^S\sum_{i\in N^F} v_i \leq T^L \tag{E.10}$$

$$x_{ij}\in\{0,1\} \qquad (i,j)\in A^1 \tag{E.11}$$

$$u_o = \{0,1\} \qquad i\in V^F, o\in O_p \tag{E.12}$$

$$v_i = \{0,1\} \qquad i\in V^F \tag{E.13}$$

Appendix F

The SOP-DR-2 formulation

Sets

W	$W = \{0, \dots, 2\bar{P} + 1\}$	Set of all nodes. Two nodes i and $i + \bar{P}$ are coupled to a platform and $\bar{P}$ is the number of platforms
W^F	$W^F = \{1, \dots, 2\bar{P}\} \subseteq W$	Set of nodes coupled to platforms (offshore facilities)
W^D	$W^D = \{1, \dots, \bar{P}\} \subseteq W$	Set of delivery nodes coupled to platforms
W^P	$W^P = \{\bar{P} + 1, \dots, 2\bar{P}\} \subseteq W$	Set of pickup nodes coupled to platforms
O_i	$i \in W^F$	Set of orders for node i
A^2	$(i, j) \in A^2, i, j \in W, i \neq j$	Set of arcs, from node i to node j

Parameters

K		The vessel deck capacity given in square meters
Q_o	$i \in W^F, o \in O_i$	Demand requirement for order o in square meters
${C_o}^L$	$i \in W^F, o \in O_i$	Lateness cost due to an order o not being served
C^S		Sailing cost per distance travelled
$\bar{D}_{ij}$	$(i, j) \in A^2$	Extended distance matrix that copes with the possibility of platforms being visited twice.
S		Operating speed
T^S		Service duration
T^L		Voyage duration limit

Variables

u_o	$i \in W^F, o \in O_i$	1 if order o is served, 0 otherwise
l_i	$i \in W$	Load on board the vessel leaving node i
v_i	$i \in W^F$	1 if node i is served, 0 otherwise
x_{ij}	$(i, j) \in A^2$	1 if the vessel travels from node i to j, 0 otherwise

Model

$$minimize \quad \sum_{i \in W^F} \sum_{o \in O_i} C_o{}^L (1 - u_o) + \sum_{(i,j) \in A^2} C^S \overline{D}_{ij} x_{ij} \tag{F.0}$$

s.t.

$$\sum_{j \in W} x_{0,j} = 1 \tag{F.1}$$

$$\sum_{i \in W} x_{i,2\bar{P}+1} = 1 \tag{F.2}$$

$$\sum_{j \in W} x_{ij} = v_i \qquad i \in W^F \tag{F.3}$$

$$\sum_{i \in W} x_{ij} = v_j \qquad j \in W^F \tag{F.4}$$

$$v_i \geq u_o \qquad i \in W^F, o \in O_i \tag{F.5}$$

$$l_0 = \sum_{i \in W^D} \sum_{o \in O_i} Q_o u_o \tag{F.6}$$

$$0 \leq l_i \leq K \qquad i \in W \tag{F.7}$$

$$l_j \geq l_i - \sum_{o \in O_j} Q_o u_o - (1 - x_{ij}) K \qquad i \in W, j \in W^D, i \neq j \tag{F.8}$$

$$l_j \geq l_i + \sum_{o \in O_j} Q_o u_o - (1 - x_{ij}) K \qquad i \in W, j \in W^P, i \neq j \tag{F.9}$$

$$\sum_{i,j \in S} x_{ij} \leq |S| - 1 \qquad S \subset W^F, |S| \geq 2 \tag{F.10}$$

$$\frac{1}{S} \sum_{(i,j) \in A^2} \overline{D}_{ij} x_{ij} + T^S \Big(\sum_{i \in N^F} v_i - \sum_{\substack{(i,j) \in A^2 | \\ j = i + \bar{P}}} x_{ij} \Big) \leq T^L \tag{F.11}$$

$$x_{ij} \in \{0, 1\} \qquad (i,j) \in A^2 \tag{F.12}$$

$$u_o = \{0, 1\} \qquad i \in W^F, o \in O_i \tag{F.13}$$

$$v_i = \{0, 1\} \qquad i \in W^F \tag{F.14}$$

Appendix G

Digital attachments

The following contents can be found in the attached .zip file:

- The report (Thesis.pdf)
- The implemented models
    - Level 1 model (Level1.mos)
    - Level 2 model (Level2.mos)
    - Level 3.1 model (Level3.1.mos)
    - Level 3.2 model (Level3.2.mos)
- Input files for the Capos basin test cases
    - Level 1 input files (Level1.txt)
    - Level 2 input files (Level2.txt)
    - Level 3.1 input files (Level3.1.txt)
    - Level 3.2 input files (Level3.2.txt)
- Distance matrices (Distances.xlsx)
- Output data for all analyses conducted in the computational study (Output)