

**MULTI OBJECTIVE OPTIMIZATION MODEL FOR
ROBUST CRUDE OIL TERMINAL SCHEDULING**

BY

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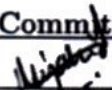
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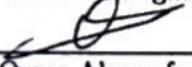
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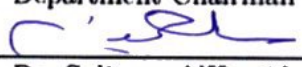
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To Aysha

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THESIS ABSTRACT

NAME: Ahmed M. AlMajed
TITLE OF STUDY: Multi Objective Optimization Model for Robust Crude Oil Terminal Scheduling
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In this work we conduct a comprehensive analysis of the crude oil export scheduling problem from the supplier's point of view, taking into account several aspects that impact the scheduling process. The thesis will focus on theoretical viewpoints as well as practical applications in order to offer an in-depth understanding of this complex problem. A novel Mixed Integer Linear Programming (MILP) model is developed for the scheduling problem, which is solved utilizing several techniques for both single and multi-objective methods. The proposed model inherently involves conflicting objectives. The multi-objective approach produced better solutions, that are aligned with business requirements and easier to interpret than the single-objective approach. Two methods for the multi-objective models were explored, the hierarchical and the weighted Tchebycheff, and their results were discussed in this thesis.

CHAPTER 1

INTRODUCTION

Crude oil is one of the most widely traded commodities worldwide, the market for it is quite competitive. Crude oil has seen continuously rising demand throughout the years, and it is expected to do so going forward. Fig.1.1 illustrates the demand of crude oil worldwide from 2005 to 2022 with a forecast of 2023 (Aizarani, 2023). This demand is generated by a number of industries, including those involved in manufacturing, transportation, and energy.

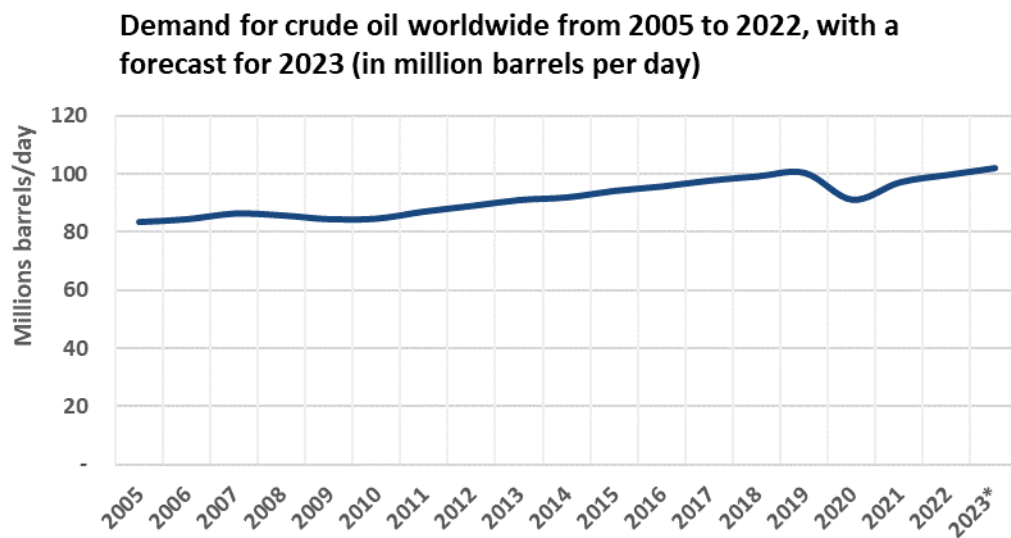


Figure 1.1: Crude Oil Demand Worldwide

1.1 Crude Oil Supply Chain

The crude oil export scheduling problem falls under a broader topic, is the energy supply chain. Figure 1.2 shows how the problem of interest is embedded to more specified topics under the energy supply chain umbrella.

The crude oil supply chain usually divided into two segments, upstream and downstream. Each segment includes a large network of equipment and facilities for crude oil production, treatment, processing and transportation. In the upstream segment, the crude oil produced from oil fields and sent to be treated in oil and gas separation plants where the gas and water associated with the crude oil are removed. The downstream segment starts with treated crude oil that supplies different facilities through pipelines. Those facilities can be refineries where the crude oil is processed, or crude oil terminals (COT) where it is stored and shipped to customers using oil ships (Hussain et al., 2006; Azadeh et al., 2017).

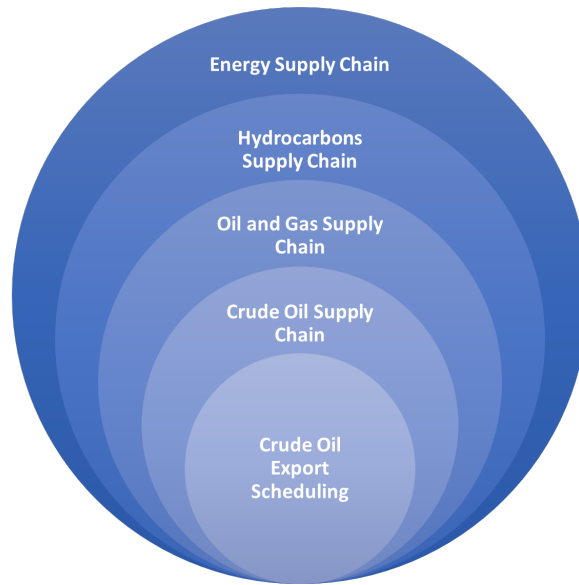


Figure 1.2: Crude Oil Supply Chain

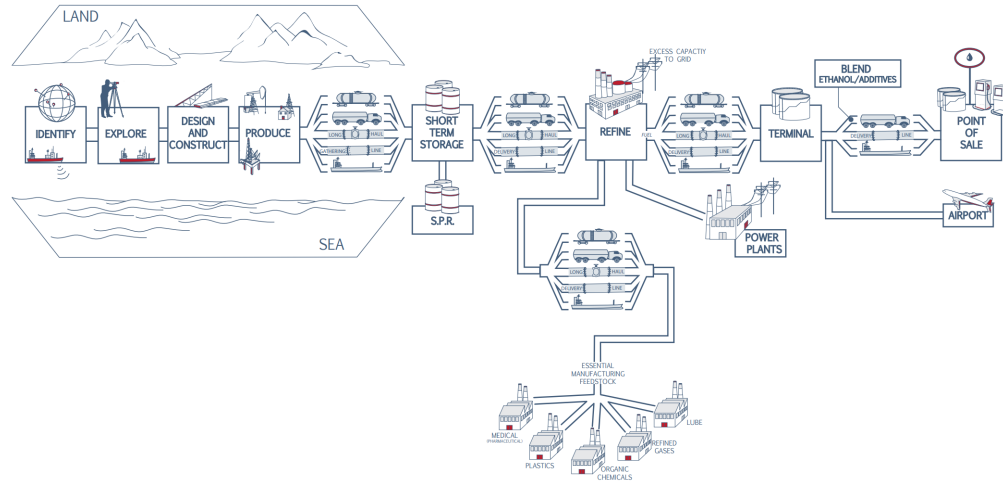


Figure 1.3: Crude Oil Supply Chain (source: www.energyinfrastructure.org)

In Figure 1.3 an illustration of the complex crude oil supply chain showing the upstream on the left hand side, beginning with crude exploration and extraction. After that, the downstream starts from crude refining to usable products such as diesel and naphtha, or to be processed further in chemical plants.

In (Hussain et al., 2006), they explained a number of logistical challenges in the crude oil supply chain. Due to the global nature of the crude oil market, customers and suppliers can be very far from each other where oil ships are required to transport the crude oil through the sea. Additionally, customers may request to load their oil ship on a specific date in order to optimize their refinery production schedule.

According to (Magalhaes et al., 2004), refineries' schedulers perform multiple activities to optimize their production schedule, such as:

1. Crude Receipt and Blending.
2. Process Units Operational Modes.
3. Inventory Management.

4. Blending.

As a part of the refinery inventory management, maintaining the availability of raw materials, i.e. crude oil, is essential for a smooth production flow, and that is directly linked to the date they request to load their oil ships while considering their routes and time to reach their destinations. Hence, allocating the loading time for the oil ships should be as close as possible to the customers' requested date to avoid any inconvenience in their operations.

1.2 Crude Oil Terminal Operation

There are two types of Crude Oil Terminal system (COTs), onshore and floating marine terminals; each one has its own advantages and disadvantages, however they both have the same logistics and operations from a scheduling point of view (Stewart, 2021). Figure 1.4 shows an example of the crude oil terminal where crude carriers are aligned on the berths to load their cargos. A COTs system consists of:

- Feed lines, supplying product to the terminal.
- Storage tanks, and water handling units.
- Loading systems, supplying products from tanks to ships.
- Berths, where a ship can be secured and load the product.

And the COTs operations are:

- Crude Receiving:** Crude oil is supplied to the terminal through pipelines, and depending on the infrastructure of the facility and the supplier capability, the

terminal can receive multiple products simultaneously, or a single product at a time (Stewart, 2021).

- ii **Crude Storage:** Crude oil is stored in crude tanks, and their capacity corresponds to the expected production rate to operate the terminals safely and to reduce product-handling costs. The number of tanks is allocated for a specific product to optimize their expected turnover. Also, some tanks can only handle a limited number of products out of the available ones due to infrastructure limitations (Stewart, 2021).
- iii **Crude Settling:** Usually, crude arrives at the terminal with associated water. As soon as the crude is stored safely, oil-water separation by gravity starts in the tanks. After several hours, excessive water then collected from the tanks to the water collection pond or to be sent to the oily water processing unit (Stewart, 2021).
- iv **Crude Loading:** Upon crude carrier arrival at the terminal, and after finishing administrative work such as documentation, inspection, and verification, cargo hoses are connected to the carrier to start loading their cargo from the tanks. Additionally, the rate at which cargo is loaded into the carrier depends on the terminal's available pumping capacity. Moreover, crude carriers come in different sizes, and may load single or multiple cargos based on the customer's requirements. Terminals are committed to load the cargos in a timely manner to avoid demurrage and operation interruption (Stewart, 2021). Ships receive their cargo through a loading system, where loading systems are a collection

of pumps and pipes that supply cargos to the carriers. Usually, each loading system is used for a single product, otherwise flushing the pipeline is needed before using the system for another product.



Figure 1.4: Crude Ship Loading (source: www.vopak.nl)

CHAPTER 2

LITERATURE REVIEW

2.1 Scheduling Problems

Scheduling is one of the core areas in the field of operations research. Although it is a topic that has been discussed in the literature for many decades, it is still a very challenging topic even with today's computational power. Scheduling process deals with the feasibility of allocating available resources over a period of time to achieve a specific task (Grossmann and Pinto, 1998). A full understanding of the type and amount of available resources is crucial in defining the problem in order for it to be solved. In a classical scheduling problem, resource allocation and job sequencing are the main logical constraints (Baker and Trietsch, 2013). Additional logical constraints will be needed based on the specifics and nature of the problem. Scheduling problems can be found in many fields such as operations scheduling, project management, information technology, healthcare, and many more (Brajković et al., 2018). According to (Grossmann and Pinto, 1998; Li et al., 2021), scheduling problems can be formulated and solved differently based on a number of factors:

1. The problem topology: *topology is how the resource and flows are related to each other*, can be a single stage, multiple stage or network.
2. Material flow: Fixed lots or Network flow.
3. Time representation: discrete or continuous.
4. Objective: improve economics, optimize operations or inventory and resource management.
5. Scheduling mode: deterministic scheduling or stochastic with or without uncertainty.

Many scheduling problems can be modeled as mathematical models, many textbooks talked about scheduling problems and introduced the classical scheduling problems, (Baker and Trietsch, 2013) discussed the following:

1. Single Machine Sequencing Problem.
2. Parallel Machines Models
3. Flow Shop Scheduling
4. The Job Shop Problem

Those classical problems are usually the basis for the many variants of the scheduling problems. Scheduling problems usually deal with binary variables that *assign* a resource to a time slot. In (Grossmann and Pinto, 1998) they discussed multiple classes of models that deal with this problem: single-unit assignment and multiple-unit assignments based on time slots or event times.

2.2 Crude Oil Supply Chains Planning and Scheduling

In the area of the crude oil supply chain, many mathematical programming models are discussed in the literature for planning and scheduling problems (Lima et al., 2016). When discussing the planning and scheduling problems, the first thing to base the problem on is the planning type; strategic, tactical or operational. Each type has a different modeling approach that suits its objectives.

2.2.1 Strategic Planning for Crude Oil Supply Chains

A strategic plan for the crude oil supply systems can be related to designing the supply chain to determine the supply facilities locations, distribution centers capacity planning and mode of transportation. Many mathematical programming models, related to the strategic planning for the crude oil supply chain, are discussed in the literature. (Kazemi and Szmerekovsky, 2015) proposed a deterministic mixed integer linear programming model for a multi-echelon multi-product downstream petroleum supply chain to minimize the total cost to produce and transport the product for strategic planning. In (Fernandes et al., 2013), the paper proposed a mixed integer linear programming model that optimizes multi-entity, multi-echelon, multi-product, and multi-transportation downstream Petroleum supply chain network with shared installations, resource capacities, supply sources and demand requirements in terms of depot locations, capacities, transportation modes, routes and network affectations for long term planning.

2.2.2 Tactical Planning for Crude Oil Supply Chains

A tactical plan for the crude oil supply systems is related to supply plans for existing infrastructure, that are concerned with long-term planning to enhance facilities utilization and minimize distribution cost by choosing the best supply mode available. Also, in the literature, many papers discussed uncertainty in demand and prices for a tactical setting. In (Qiu et al., 2022), they discussed how to handle the imbalance in supply and demand for oil products and to optimize the products transportation for a multi-mode transportation scheme for a large-scale network. (Pudasaini, 2021) proposed a mathematical model for strategic and tactical planning of downstream petroleum supply chain (DPSC) networks with demand uncertainty using a two-stage stochastic approach based on scenarios. The model is optimizing the network for multiple distribution centers, products and transportation with transshipment between centers. The authors in (Lima et al., 2021) proposed a fuzzy approach to incorporate uncertainty in a Mixed Integer Linear Programming (MILP) model that determines the network design and distribution plan.

2.2.3 Operational Planning for Crude Oil Supply Chains

The operational planning for the crude oil supply chain is related to the short and mid-term planning that involves explicit instructions and schedules that minimize the transportation and product handling costs while meeting the required demand. In the literature, many papers discussed operational planning for the crude oil supply chain, some of them introduced uncertainty in demand as a challenge and proposed different

methods to incorporate it. In (Al-Othman et al., 2008), The authors discussed an approach to incorporate uncertainty in demand and prices, using scenario analysis, for a petroleum supply chain that optimizes crude production, processing and distribution. The Authors in (Wang et al., 2020) discussed an approach to manage the reliability of the supply system and the demand uncertainty by proposing a number of scenarios that cover the whole supply chain reliability. A MILP model was used to optimize the supply plan and a Monte Carlo simulation was used to assess the reliability. The authors in (Attia et al., 2019) discussed a multi-objective optimization approach for an oil and gas upstream operations planning, using an Improved Augmented ϵ -Constraint algorithm, that generates an efficient Pareto-optima. Table 2.1 summarizes the paper reviewed related to crude oil supply chain.

Table 2.1: Crude Oil Supply Chain Papers Reviewed

Paper	Application	Modeling Approach	Planning
Kazemi and Szmerekovsky (2015)	Petroleum supply chain (PSC) network design to determine the optimal distribution center (DC) locations, capacities, transportation modes, and transfer volumes.	Deterministic MILP	Strategic
Fernandes et al. (2013)	Strategic design and planning of the downstream PSC network that determines optimal depot locations, capacities, transportation modes, routes and network affectations for long-term planning	Deterministic MILP	Strategic
Qiu et al. (2022)	Resource adjustment and transportation optimization in oil product primary logistics	LP	Tactical

Pudasaini (2021)	Refined Products supply planning with uncertainty in demand for strategic and tactical natures. The strategic part is to determine if additional storage capacity is needed. The tactical part is for shipment distribution.	Stochastic Multi-objective MILP	Strategic & Tactical
Al-Othman et al. (2008)	Multi-period operational planning for a crude oil production and processing with demand and prices uncertainty	Stochastic LP	Operational
Lima et al. (2021)	Strategic and tactical planning of a downstream oil supply chain subject to different sources of uncertainty.	Fuzzy MILP	Strategic & Tactical
Wang et al. (2020)	Refined Products supply chain demand management for operational planning.	Scenario based MILP & Monte Carlo simulation	Operational
Attia et al. (2019)	Optimizing Upstream operations for Oil and Gas Supply chain	Multi-objective Optimization model Using ϵ -Constraint method	Tactical

2.3 Maritime Scheduling

Maritime scheduling is the process of matching cargo and vessels in the most efficient way possible. It is a complex task that requires balancing multiple variables, such as vessel availability, cargo type, and port schedules. Maritime schedulers are responsible for ensuring that the cargoes are delivered on time and in the most cost-effective manner possible.

According to the 2018 annual review of maritime transport by The United Nations

Conference on Trade and Development (Song, 2021), over 70% of world trade by value is transported by sea, and over 50% of that seaborne trade is transported by container ships, demonstrating the significance of the seaborne shipping industry. In 2021, 1.83 billion metric tons of crude oil were shipped throughout the world by sea (Department, 2023), which is due to the importance of crude oil as it fuels the global economy. The maritime operation can be divided into five value-adding segments related to the logistical operations (Song, 2021):

- Freight logistics.
- Container logistics.
- Vessel logistics
- Port and Terminal logistics.
- Inland transport logistics.

2.3.1 Port and Terminal Operations Scheduling

Improving the effectiveness and productivity of port operations is the main objective of port and terminal logistics planning. In the context of crude oil terminals, the operation planning is divided into three areas, Loading, Tank farm and Receiving areas, where each area has its own schedule to be produced. Those areas are described in the literature as Berth allocation problem (BAP), Tank Allocation Problem (TAP), and production scheduling problem for the tactical level of planning. The majority of

research in this area is for container and petrochemical terminals, however it can be applied to the crude oil terminals since their operation is similar.

In the literature, the majority of the papers are concerned with problems related to vessel routing and berth allocation in the marine supply topics. Many papers discussed the BAP in the literature, in (Golias et al., 2014), the authors introduced a solution methodology to solve a discrete berth scheduling problem via hierarchical optimization using a genetic algorithm. In (Cankaya et al., 2019), the authors formulated the Berths Assignment problem as an open shop scheduling problem and then solved using two solution methodologies, MILP and CP, constraint programming. In the paper written by (Bausch et al., 1998) the authors demonstrated a scheduling solution to assist employees in preparing the ships dispatching schedule using a Mathematical programming model and can simulate the result and provide its associated cost.

Other papers discussed vessels routing problem for marine movement. The authors in (An et al., 2019), brought a real-life problem for a petrochemical plant that ships products to customers using a few number of owned ships. The problem considers product availability and tugging operation to load the ships, then transport the product to a port of destination then return for another trip. The problem is modeled as MILP model, then an initial solution is obtained by a heuristic which is then inserted into the CPLEX solver to reduce the time needed. The authors in (Ye et al., 2017) introduced a two-level model that assigns a vessel to a task that consists of a combination of product and a destination, that maintains the demand at the destination, then the second level assigns vessels to a day to ensure no overlap between vessels operations. A vendor managed inventory system was solved by a MILP model that

was formulated as a Maritime Inventory Routing Problem in (Misra et al., 2020). The model optimizes the whole supply system considering ship movements and jetty allocation. Some papers discussed the tank-farm management as a pipeline scheduling problem. In (Relvas et al., 2006) the authors present a Mixed integer linear programming model for a tank farm inventory management for a single pipeline and multi-product problem. In the paper, they discussed the pipeline product scheduling problem to maintain a safe inventory to satisfy all customers' demand. The authors in (Castro and Mostafaei, 2017) present a new MILP formulation for straight pipelines, that schedules products in the pipeline with optimum sequence to avoid undesirable product intermixing while satisfying the demand timely. Table 2.2 summarizes the paper reviewed related to maritime scheduling.

Table 2.2: Maritime Scheduling Paper Reviewed

Paper	Application	Modeling Approach	Planning
Golias et al. (2014)	Berth Scheduling for marine container terminals with uncertainty in process timing	Robust Modeling using hierarchical optimization using genetic algorithm	Operational
An et al. (2019)	Marine fleet routing and port operations optimization for a petrochemical plant	MILP	Tactical & Operational
Cankaya et al. (2019)	Berth Scheduling for Chemical Tankers	MILP and Constraint Programming	Operational
Ye et al. (2017)	Refinery shipping operation for multiple products and multiple destination	MILP	Operational
Misra et al. (2020)	Maritime inventory routing for multiple refinery	MILP	Tactical & Operational

Seimetz Chagas et al. (2023)	Platform Supply Vessels Scheduling for Upstream Oil and Gas logistics	Decomposition using Cluster- ing and MILP	Tactical & Opera- tional
Bausch et al. (1998)	short term dispatching marine trans- port of liquid bulk product	Mathematical Model	Operational
Relvas et al. (2006)	Rescheduling of oil pipeline opera- tion to manage tank-farm inventory	MILP	Tactical & Opera- tional

2.4 Research Objective

The crude oil export scheduling problem from the supplier perspective was not investigated enough in the literature. A problem that is concerned with being customer-centric, with dynamic inventory capacity management, and integrating customers' satisfaction with safe operating levels.

The objective of my thesis is to research and investigate the crude oil terminal operations planning and scheduling, for a multi-product dynamic storage capacity problem. Producing and exporting crude oil need to be carefully planned in order to avoid tanks overfilling and supply shortage. Additionally, poor schedules may lead to customers' refinery operations interruption. Moreover, with a problem of industrial size, and a large number of variables, finding an optimum solution may be difficult. Hence, The problem will be formulated as a MILP model first, and then different methods to obtain practical feasible solutions will be explored.

CHAPTER 3

METHODOLOGY

3.1 Problem Statement

In the crude oil shipping industry, crude oil terminals play a pivotal role in maintaining the global economy by ensuring a sustainable supply of crude oil to the world. In my thesis, I will discuss optimizing the crude oil export terminal operations and oil carriers' scheduling for a case of an industrial scale. The problem will include a multi-product and single-location inventory problem with a dynamic inventory capacity that is integrated with the oil carriers scheduling problem.

In this problem, multiple crude oil grades are being handled in crude oil terminals with a continuous supply. Oil carriers need to be scheduled to load one or more products with their allocated quantity. In addition, oil carriers need to be loaded on a specific day due to their commitments, and it is desired to accommodate them on their requested day or to minimize the deviation from the requested day.

Moreover, the crude oil terminal has multiple capacitated resources such as the number of berths to serve oil carriers at the same time, different capacities for tanks related to

their location, the number of tanks that have the ability to switch their service, and the supply and loading capacity for each crude grade.

3.2 Problem Modeling

For this problem, an assignment formulation will be utilized to schedule the oil carriers. Each carrier will be assigned to a loading day, that should be as close as possible to its requested day. Hence the problem will have a discrete time representation, i.e. each day will be a slot that can take a number of oil carriers.

3.3 Assumptions

- The demand is always less than the supply including the opening inventory.
- Back-order is not allowed. Inventory levels never go below zero.
- Inventory will be aggregated per product pool for all locations.
- The number of carriers to be scheduled in a day is half of the number of available berths, this is to eliminate the possibility of overlapping carriers on the same berth in case of uncompleted loading within a day.
- The impact of changing the loading capacity in two consecutive days is negligible.

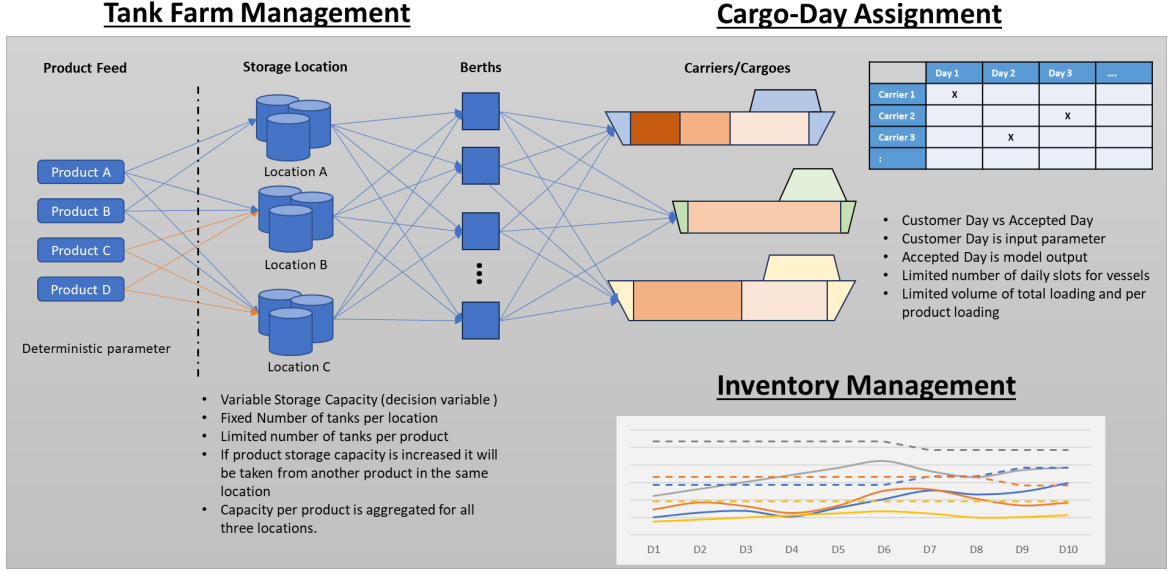


Figure 3.1: Problem Schematic

3.4 Model Formulation

Indices:

i : Crude carrier index, $i = 1, 2, \dots, n$ and $i \in I$

j : Day index, $j = 1, 2, \dots, d$ and $j \in J$

k : Product index, $k = 1, 2, \dots, p$ and $k \in P$

l : Location index, $l = 1, 2, \dots, m$ and $l \in M$

Decision Variables:

$$X_{ij} = \begin{cases} 1, & \text{If crude carrier } i \text{ is scheduled on day } j \\ 0, & \text{Otherwise} \end{cases}$$

T_{jkl} = Number of tanks in tankfarm l that stores product k in day j

r_{jk}^+ = Volume of product k violating the soft maximum constraint for inventory in day j

r_{jk}^- = Volume of product k violating the soft minimum constraint for inventory in day j

Parameters:

D_j = day j in the planning horizon = 1, 2, 3, ... , d

N_i = Oil carrier i requested loading day

C_{ik} = Cargo size of product k to be loaded on carrier i

$$P_{ik} = \begin{cases} 1, & \text{if carrier } i \text{ is asking for product } k \\ 0, & \text{otherwise} \end{cases}$$

PM_{jk} = Maximum number of cargoes of product k that can be loading in day j

$AvgC_k$ = Average cargo size for product k

$Mdel$ = Maximum number of days a carrier can be delayed

$Madv$ = Maximum number of days a carrier can be advanced

OI_{jk} = Opening inventory of product k in day j

F_{jk} = Product k feeding the terminal in day j

S_j = Maximum number of carrier to be scheduled in day j

$AvgT_{kl}$ = Average Tank size of product k in location l

$MaxT_{kl}$ = Maximum number of tanks that can store product k in location l

X_i^+ = Linearization for the absolute value function for carrier i day deviation

L_{jk} = Total product k loading in day j

Cap_{jk} = Storage capacity for product k in day j

I_{jk} = Inventory of product k in day j

TSC_{jkl} = Number of tanks added or taken out from product k service in location l in day j

TSC_{jkl}^+ = Linear representation for the absolute value function for tanks services change

Objective Function:

$$\begin{aligned}
 Min \quad Z = & m^+ * Mdel + m^{++} * Madv + \sum_{i=1}^n X_i^+ * Pr_i \\
 & + cr * \sum_{k=1}^p \sum_{j=1}^d (r_{jk}^+ + r_{jk}^-) + w * \sum_{l=1}^m \sum_{k=1}^p \sum_{j=1}^d TSC_{jkl}^+
 \end{aligned} \tag{3.1}$$

Constraints:

$$\sum_{j=1}^d X_{ij} * D_j - N_i \leq X_i^+ \quad \text{and} \quad N_i - \sum_{j=1}^d X_{ij} * D_j \leq X_i^+ \tag{3.2}$$

$$\sum_{j=1}^d X_{ij} * D_j - N_i \leq Mdel \tag{3.3}$$

$$\sum_{j=1}^d X_{ij} * D_j - N_i \geq -Madv \tag{3.4}$$

$$\sum_{j=1}^d X_{ij} = 1 \quad \forall i \tag{3.5}$$

$$L_{jk} = \sum_{i=1}^n X_{ij} * C_{ik} \quad \forall j, k \tag{3.6}$$

$$I_{jk} = OI_{jk} + F_{jk} - L_{jk} \quad \text{for } j = 1 \ \& \ \forall k \tag{3.7}$$

$$I_{jk} = I_{j-1,k} + F_{jk} - L_{jk} \quad \text{for } j \geq 2 \ \& \ \forall k \tag{3.8}$$

$$I_{jk} \leq Cap_{jk} \quad \forall j, k \tag{3.9}$$

$$I_{jk} \geq 0 \quad \forall j, k \tag{3.10}$$

$$I_{jk} \leq 0.8 * Cap_{jk} + r_{jk}^+ \quad \forall j, k \tag{3.11}$$

$$I_{jk} \geq 3 * AvgC_k - r_{jk}^- \quad \forall j, k \quad (3.12)$$

$$\sum_{i=1}^n X_{ij} \leq S_j \quad \forall j \quad (3.13)$$

$$\sum_{i=1}^n X_{ij} * P_{ik} \leq PM_{jk} \quad \forall j, k \quad (3.14)$$

$$\sum_{k=1}^p L_{jk} + L_{j+1,k} \leq LC_j + LC_{j+1} \quad \forall j \quad (3.15)$$

$$Cap_{jk} = \sum_{l=1}^m T_{jkl} * AvgT_{kl} \quad \forall j, k \quad (3.16)$$

$$T_{jkl} \leq MaxT_{kl} \quad \forall j \quad (3.17)$$

$$\sum_{k=1}^p T_{jkl} = ATanks_{jl} \quad \forall j, l \quad (3.18)$$

$$\frac{|T_{jkl} - T_{j-1,kl}|}{2} = TSC_{jkl} \quad \forall j, k, l \quad (3.19)$$

$$TSC_{jkl} \leq TSC_{jkl}^+ \quad and \quad -TSC_{jkl} \leq TSC_{jkl}^+ \quad \forall j, k, l \quad (3.20)$$

3.4.1 Crude Oil Carriers to Day Assignment

Let n and d be the number of oil carriers and number of days in the planning horizon and indices i and j are associated with them respectively, then a binary variable X_{ij} can be defined as:

$$X_{ij} = \begin{cases} 1, & \text{if crude carrier } i \text{ is scheduled on day } j \\ 0, & \text{otherwise} \end{cases}$$

and in the objective function, there will be a term that minimizes the deviation from the oil carrier requested day N_i . Since X_{ij} is a binary variable, parameter D_j is

introduced where $D_j = j$ for $j = 1, 2, \dots, d$ to calculate the deviation from the requested day N_i . The deviation calculation is shown in Equation 3.21.

$$|\sum_{j=1}^d X_{ij} * D_j - N_i| \quad \forall i \quad (3.21)$$

However, Equation 3.21 is not a linear equation hence it needs to be linearized by introducing X_i^+ as shown in Equation 3.2. Additionally, there is a maximum number of days that an oil carrier can deviate, *delayed or advanced*, hence $\sum_{j=1}^d X_{ij} * D_j - N_i$ have an upper limit of $Mdel$ and a lower limit of $Madv$. Equation 3.3 and Equation 3.4 show how this is implemented. Noting that $\sum_{j=1}^d X_{ij} * D_j - N_i$ can be positive or negative, thus its lower bound will be greater than the negative of $Madv$ as shown in Equation 3.4. Finally, the last constraint, Equation 3.5, will ensure all carriers are assigned to a loading day only once, Equation 3.2 to Equation 3.5 cover the carrier to day assignment formulations, which can be considered as the un-capacitated scheduling model. However, for the researched problem there are multiple capacities that need to be considered to create the loading schedule.

3.4.2 Inventory Capacity Constraints

Let variable I_{jk} which calculates the inventory for product k in day j as shown in Equation 3.7 and Equation 3.8. Where L_{jk} is the total loaded quantity of product k in day j as shown in Equation 3.6 and F_{jk} is the amount of product k feeding the terminal on day j . Moreover, parameter OI_k is the opening inventory for product k i.e. it will be considered only when $j = 1$.

Now introducing variable Cap_{jk} as the storage capacity for product k in day j , *it is a variable since it will be dynamically changed as shown in Equation 3.16*. Now, I_{jk} is maintained based on two kinds of constraints, soft constraints that are allowed to be violated, *with a penalty*, and hard constraints related to the physical storage capacity. The hard constraints are straight forward as shown in Equation 3.9 and Equation 3.10. To address the soft constraints, it is needed to introduce two dummy variables r_{jk}^+ and r_{jk}^- to allow the model to violate upper and lower bounds respectively with a penalty cr that will be included in the objective function. Then those constraints can relate to a percentage of the capacity or a predefined safe max and min inventory levels. Here, Equation 3.11 is related to the soft max constraint and it will be based on 80% of the available capacity. Additionally, Equation 3.12 is related to the soft min constraint and it is based on three times the average cargo size of product k , during the planning horizon. $AvgC_k$ is used to calculate the average cargo size in the planning horizon as shown in Equation 3.22.

$$AvgC_k = \frac{\sum_{i=1}^n C_{ik}}{\sum_{i=1}^n P_{ik}} \quad (3.22)$$

Where $\sum_{i=1}^n C_{ik}$ is the total volume of product k planned to be exported and $\sum_{i=1}^n P_{ik}$ is the total number of cargoes of product k planned to be loaded for all available carriers.

3.4.3 Crude Carrier and Cargo Scheduling Constraints

Let S_j be the maximum number of carriers allowed to be scheduled to load on the same day, then the number of crude carriers to be assigned on day j is shown in Equation 3.13.

Additionally, since each loading system can handle one product at the same time, and due to the available capacity of the loading systems, limiting the number of cargoes of the same product to be loaded on the same day is needed. Let P_{ik} be an input such that

$$P_{ik} = \begin{cases} 1, & \text{if carrier } i \text{ is asking for product } k \\ 0, & \text{otherwise} \end{cases}$$

and PM_{jk} to be maximum number of cargoes lifted of product k on day j . Equation 3.14 shows how to limit the number of cargoes of the same product to be loaded on the same day.

3.4.4 Loading Capacity Constraints

Crude oil terminals load crude carriers through loading lines using pumps. Those loading lines have a capacity to transfer the crude oil from the tanks to the carrier, based on their size and pumping rate. The logic can be formulated by introducing LC_j as the maximum loading capacity for the crude oil terminal for day j , and using L_{jk} that was introduced in Equation 3.6. However, since large carriers usually take more than one day and less than two days to be fully loaded, *and since the model is based on a discrete-time representation*, keeping track of the loaded quantity for

two consecutive days and maintaining it below the loading capacity for two days is required. Equation 3.15 shows how this logic is implemented.

3.4.5 Storage Capacity Constraints

In this dynamic system, storage capacity can be planned to be altered as needed, based on the storage tanks to product allocation on day to day basis. Introducing integer variable T_{jkl} to be the number of tanks in tank farm l , and $l \in M$, that stores product k on day j . The crude grades are handled in multiple tank farms, each of which has a different capacity, number of tanks, and specific crude grades that can be handled there.

In Equation 3.16, Cap_{jk} is defined as the assigned storage capacity for product k in day j , and $AvgT_{kl}$ is the average tank size located in tank farm l that can handle product k . By multiplying T_{jkl} by $AvgT_{kl}$ it will provide a good indication of the calculated capacity at location l to store product k on day j .

Also, there is a limited number of tanks at tank farm l that can handle product k . Let $MaxT_{kl}$ be the maximum number of tanks, at tank farm l that can handle product k , then Equation 3.17 limits the number of tanks assigned to product k on day j in tank farm l to be less than or equal $MaxT_{kl}$. Finally, all available tanks must be used, Equation 3.18 maintains the usage of all available tanks.

3.4.5.1 Tracking Number of Tanks Service Change

Although the system allows for change of the tank service when needed, it is not preferable and the number of tank service changes needs to be minimized. Equa-

tion 3.19 captures the number of tanks' service changes between two consecutive days utilizing variable TSC_{jkl} . Additionally, as the change may include adding or removing a tank from the service of product k , TSC_{jkl} will represent the absolute difference in the number of tanks required to serve product k at tank farm l between days j and $j - 1$.

Moreover, Equation 3.19 shows the calculation of the number of tanks is divided by two to avoid double counting the number of tanks service reassignment. Because once the count of tanks that serve a product increases by one the count of tanks that serve another product will decrease by one. This means the total number of service changes will be 2, whereas it is only one tank that changed its service. This will not play a big role in the model since it is only dividing by a constant, however, it is more practical as it will indicate the number of tanks that changed their service. Furthermore, in order to linearize the equation, one additional variable TSC_{jkl}^+ needs to be introduced with two additional constraints as shown in Equation 3.20.

3.4.6 Objective Function

There are several penalties and metrics that need to be addressed as part of the objective function, those are:

- Pr_i : Priority of carrier i , the higher the priority the less the deviation from the requested date.
- w : Penalty of changing tank service.
- cr : Penalty of using the dummy variables for violating soft inventory limits.

The objective function will be as shown in Equation 3.23:

$$\text{Min } Z = \sum_{i=1}^n X_i^+ * Pr_i + w * \sum_{l=1}^m \sum_{k=1}^p \sum_{j=1}^d TSC_{jkl}^+ + cr * \sum_{k=1}^p \sum_{j=1}^d (r_{jk}^+ + r_{jk}^-) \quad (3.23)$$

which minimizes the deviation of the carriers' requested loading date, the inventory limits violation, and the number of tanks that switched their service. However, the objective presented in Equation 3.23 is not unified, since each component is measured based on different units. The first section which is related to the carriers' deviation days is measured in days, the second section which is related to tanks service change is in the number of tanks, and finally, the last section which is related to the violation of the inventory soft limits is in volume.

Unifying the objective function can be easily done by converting the three sections to volumes, by multiplying the deviation days by the carrier cargo size, and multiplying the average tank size for product k by the number of tanks service change as shown in Equation 3.24.

$$\begin{aligned} \text{Min } Z = & \sum_{i=1}^n X_i^+ * \sum_{k=1}^p C_{ik} * Pr_i \\ & + w * \sum_{l=1}^m \sum_{k=1}^p \sum_{j=1}^d TSC_{jkl}^+ * AvgT_{kl} \\ & + cr * \sum_{k=1}^p \sum_{j=1}^d (r_{jk}^+ + r_{jk}^-) \end{aligned} \quad (3.24)$$

Although, the units are unified, notice that the objective presented in Equation 3.24, will give more priority to carriers' with larger volumes to be scheduled first and smaller tanks to be service switched. This logic is not in alignment with the business require-

ments, as the volume of crude carrier and the size of the tank do not factor in the prioritization of the carriers or the tanks.

3.4.6.1 Robust Approach Against Infeasibility

After experimenting with a number of datasets, it was found that the main cause of returning an infeasible solution is that the model cannot schedule all carriers within the predefined limits, $Mdel$ & $Madv$. To counter this issue, the model will need to minimize the maximum days delayed and advanced, hence including the upper and lower limits, $Mdel$ and $Madv$ in the objective function with a high penalty, m^+ , for $Mdel$ and a higher one, m^{++} , for $Madv$ since accepting advancing the loading date may not be acceptable to the customers. Hence, the objective function will be as shown in Equation 3.1.

CHAPTER 4

MODEL EXPERIMENTATION & PRELIMINARY RESULTS

In this section, a small instance of the problem will be produced to be solved and analyzed using the model proposed.

4.1 Experimental Data

The experimental data consists of 5 days and 15 crude carriers to be scheduled. In addition, the products feed to the terminal shown in Table 4.2, and storage capacity shown in Table 4.5, will be provided along with the loading and number of carriers per day capacities shown in Table 4.4. For experimental purposes three cases will be examined, where the carriers requested loading day is based on a given schedule, fixed on the first day for all of them, and fixed on the last day for all of them, for Case 1, Case 2 and Case 3 respectively, as shown in Table 4.1. The main objective is to test the model's robustness against the requested loading days provided by customers.

Moreover, the terms in the objective functions are assumed equally important, and their penalties are equal, except for the maximum days delay and advanced variables, $Mdel_i$ and $Madv_i$, which are 1,000 and 99,999 respectively.

Table 4.1: Carrier Details

Carrier ID	Product				Requested Loading Day		
	A	B	C	D	Case 1	Case 2	Case 3
1	250		500		1	1	5
2		200	500		1	1	5
3	250			320	2	1	5
4		300		200	1	1	5
5			200		1	1	5
6			500		2	1	5
7	500	400			1	1	5
8		200	300		4	1	5
9	250		150		1	1	5
10		300	110	220	1	1	5
11		110	220		2	1	5
12	100	500	300		1	1	5
13			220	110	5	1	5
14	350	220	220		3	1	5
15				300	1	1	5

Table 4.2: Product Feed to Terminal

Feed to Terminal				
Day	A	B	C	D
D1	240	500	780	200
D2	240	500	780	200
D3	240	500	780	200
D4	240	500	780	200
D5	240	500	780	200

Table 4.3: Products Details

Product	A	B	C	D
Opening Inventory	500	800	500	500
Number of Cargoes Per Day	2	2	3	2

Table 4.4: Operations Capacity

Daily Loading Capacity	2500
Carriers Per day	5

Table 4.5: Tanks Location and Size

Location	LA	LB	LC
Number of Tank Available	10	7	8
Average Tank Size Per Product			
A	500	350	200
B	500	480	200
C	500	300	0
D	500	400	0
Number of Tanks Per Product			
A	7	7	8
B	10	7	8
C	10	7	0
D	7	7	0

4.2 Result

The results obtained after solving the model for all the above three cases are presented in the following tables and figures. The following subsections provide an overview of the tables and the figures.

4.2.1 Carrier Loading Day and Deviation From Requested Day

Table 4.6 shows the scheduled day for each carrier, $X_i * D_j$, and its deviation from the requested day N_i . It is worth noting that the proposed linearization for the absolute value function for the variable sd_i , where $sd_i = \sum_{j=1}^d X_{ij} * D_j - N_i$, matches variable X_i^+ .

4.2.2 Quantity Loaded, Inventory, and Storage Management

In this section, the inventory and loaded quantity are illustrated for the three cases, charts from Figure 4.1 to Figure 4.9, show how the model generated the loading plan to comply with the available storage capacity.

Table 4.6: Experimental Result - Carriers Loading Day Deviation

Carrier ID	Case 1				Case 2				Case 3			
	N_i	$X_i * D_j$	X_i^+	sd_i	N_i	$X_i * D_j$	X_i^+	sd_i	N_i	$X_i * D_j$	X_i^+	sd_i
1	1	4	3	3	1	4	3	3	5	3	2	-2
2	1	3	2	2	1	5	4	4	5	2	3	-3
3	2	5	3	3	1	5	4	4	5	5	0	0
4	1	2	1	1	1	3	2	2	5	4	1	-1
5	1	1	0	0	1	1	0	0	5	5	0	0
6	2	2	0	0	1	3	2	2	5	4	1	-1
7	1	4	3	3	1	5	4	4	5	5	0	0
8	4	5	1	1	1	2	1	1	5	5	0	0
9	1	3	2	2	1	3	2	2	5	4	1	-1
10	1	4	3	3	1	4	3	3	5	3	2	-2
11	2	2	0	0	1	3	2	2	5	3	2	-2
12	1	3	2	2	1	2	1	1	5	2	3	-3
13	5	5	0	0	1	2	1	1	5	2	3	-3
14	3	5	2	2	1	4	3	3	5	4	1	-1
15	1	4	3	3	1	5	4	4	5	5	0	0

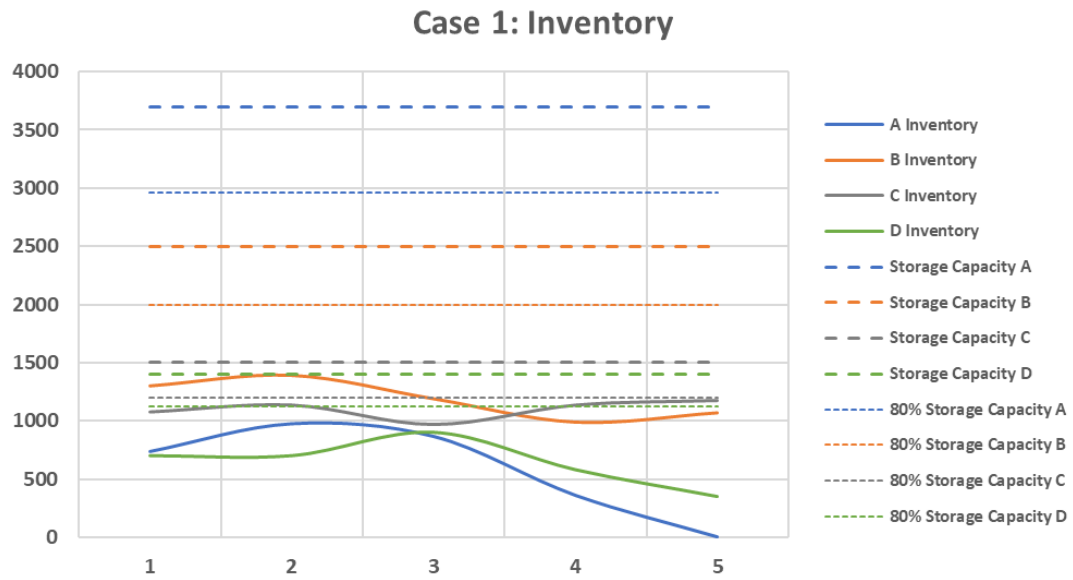


Figure 4.1: Case 1 Inventory

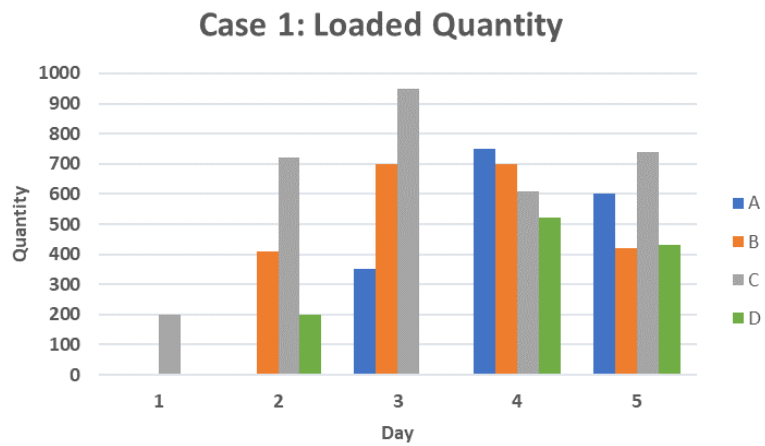
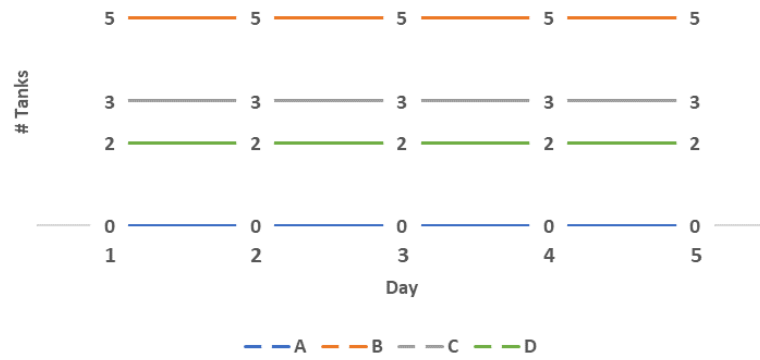
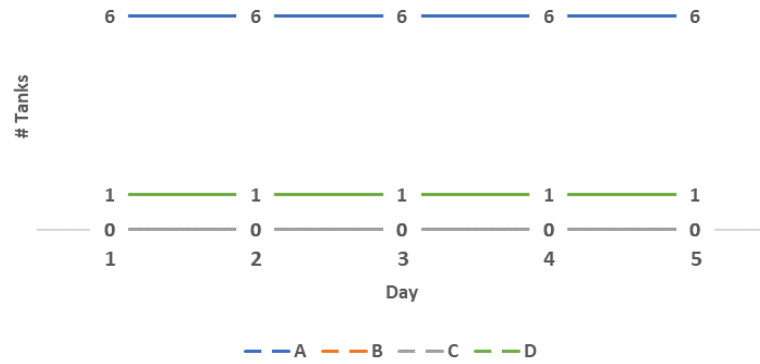


Figure 4.2: Case 1 Loaded Quantity

CASE 1: LA TANKS MANAGEMENT



CASE 1: LB TANKS MANAGEMENT



CASE 1: LC TANKS MANAGEMENT

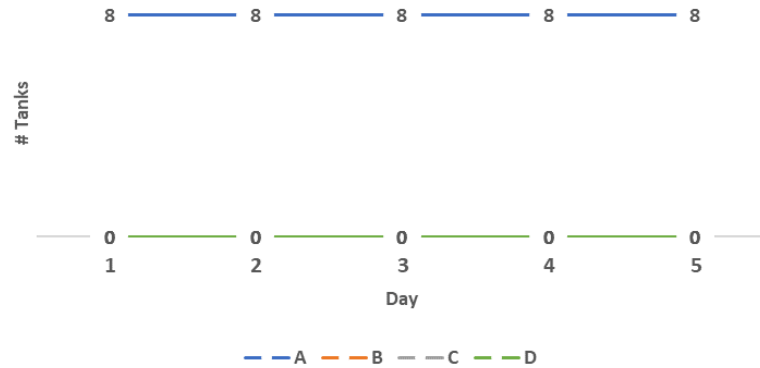


Figure 4.3: Case 1 Tanks Management

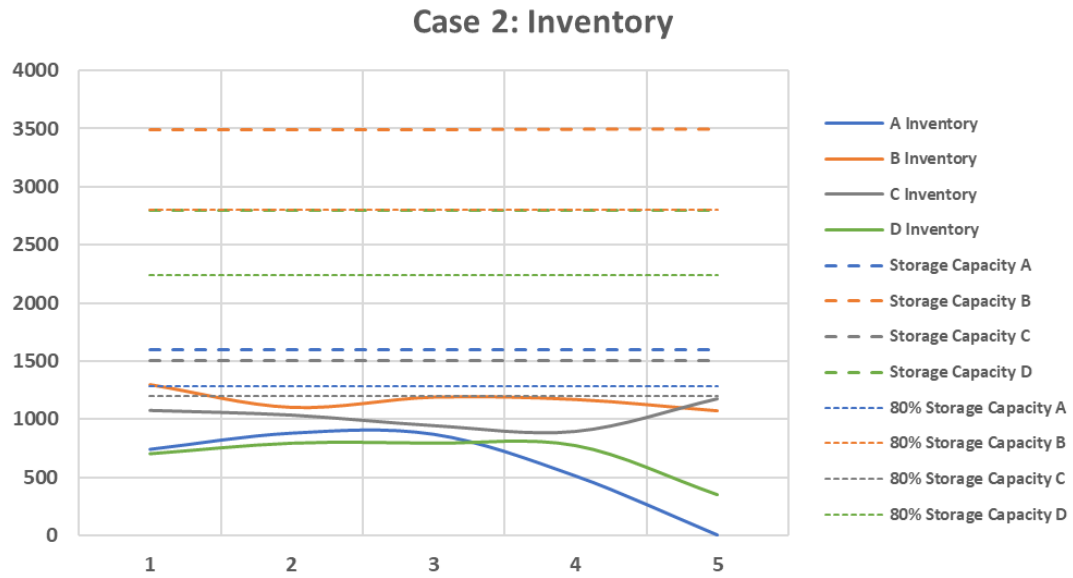


Figure 4.4: Case 2 Quantity Loaded, Inventory and Storage Management

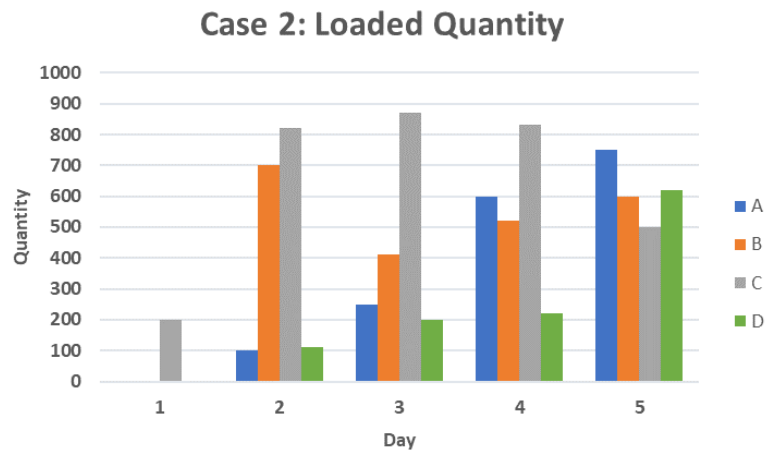
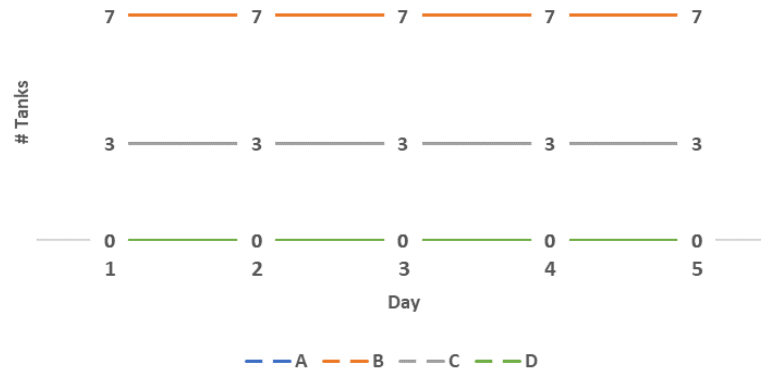
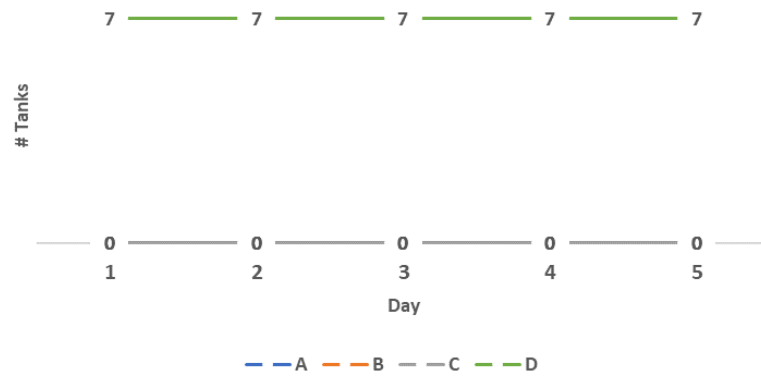


Figure 4.5: Case 2 Loaded Quantity

CASE 2: LA TANKS MANAGEMENT



CASE 2: LB TANKS MANAGEMENT



CASE 2: LC TANKS MANAGEMENT

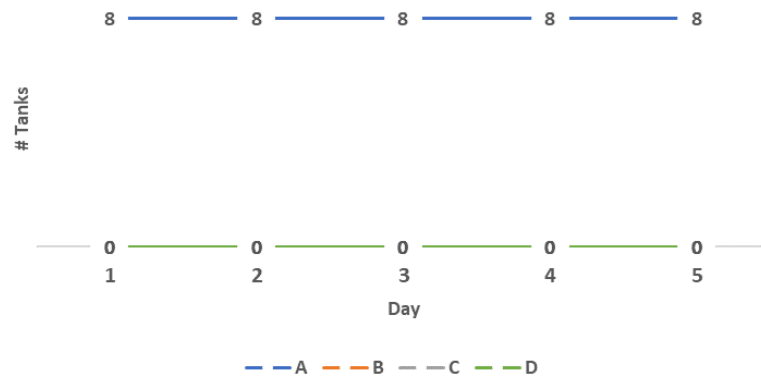


Figure 4.6: Case 2 Tanks Management

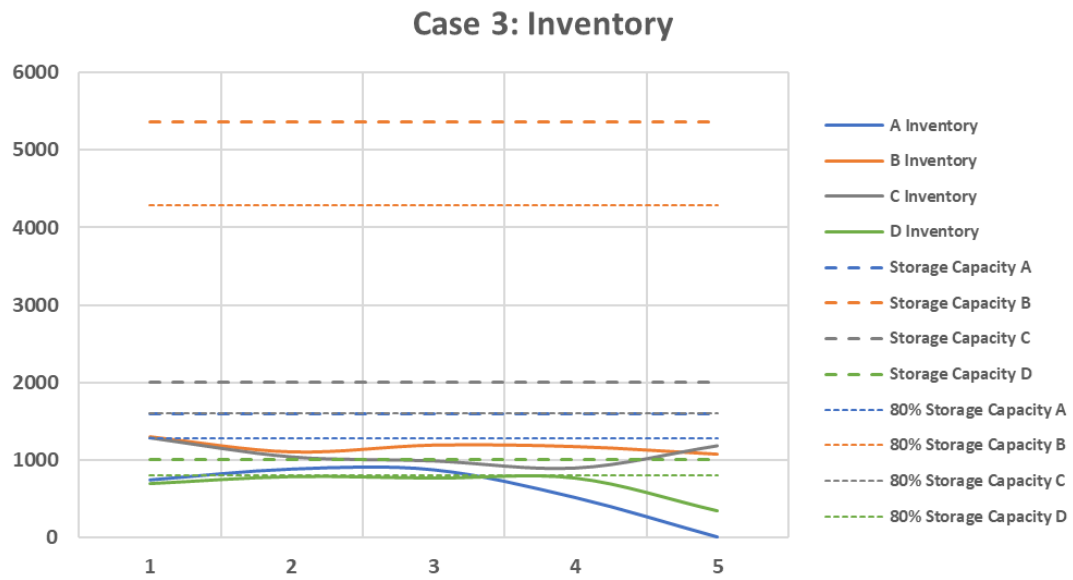


Figure 4.7: Case 3 Inventory

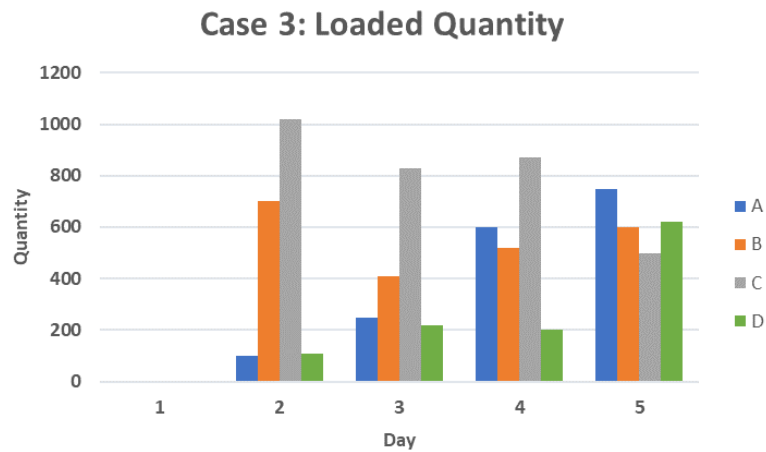


Figure 4.8: Case 3 Loaded Quantity

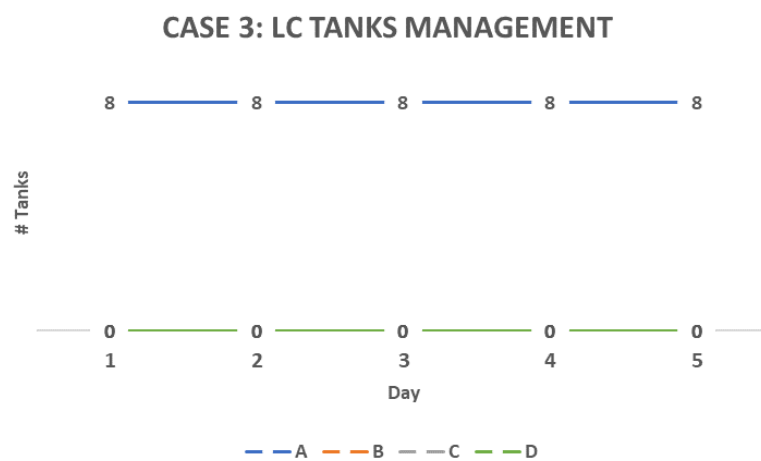
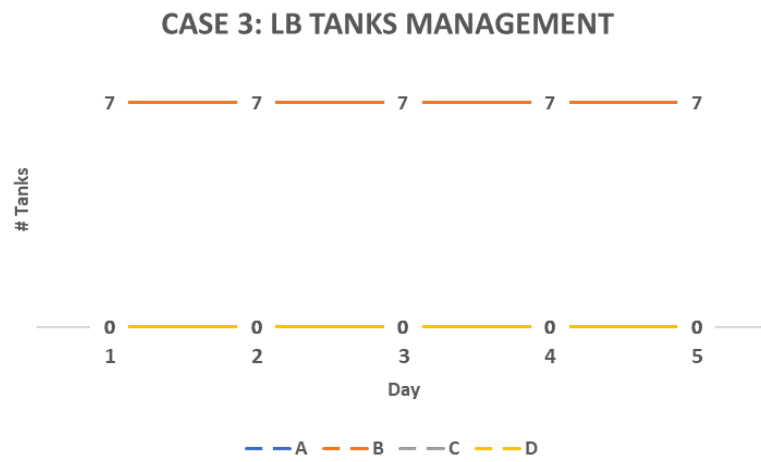
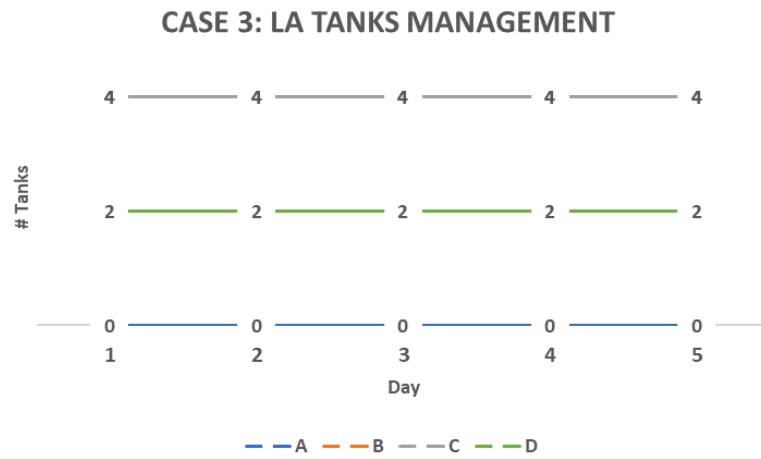


Figure 4.9: Case 3 Tanks Management

4.2.3 Case 4: Dynamically Optimize the Storage Tanks Allocation

In order to show how the model dynamically optimizes the inventory capacity limits, by allocating more storage tanks for a specific product and reducing the other, using the integer variable T_{jkl} , a fourth case is used to demonstrate this functionality. In this case, all parameters of the previous cases are used except of the requested loading day and the average tank size. The average tank size is **150** for Case 4, and it is applied for all products for all locations. Table 4.7 shows the requested loading days and the scheduled day along with their deviation:

Table 4.7: Experimental Result - Carriers Loading Day Deviation Case 4

Carrier ID	Case 4			
	N_i	$X_i * D_j$	X_i	sd_i
1	5	4	1	-1
2	5	2	3	-3
3	1	4	3	3
4	1	3	2	2
5	5	5	0	0
6	5	3	2	-2
7	5	5	0	0
8	5	4	1	-1
9	5	3	2	-2
10	1	1	0	0
11	5	3	2	-2
12	5	2	3	-3
13	1	1	0	0
14	5	5	0	0
15	1	4	3	3

The model took longer time to solve Case 4, however, it managed to satisfy all con-

straints and produced a feasible solution. Following plots, Figure 4.10 to Figure 4.12 show the result. Figure 4.10 shows how the storage capacity changes to accommodate the product. Also, it shows how the model tries to allocate enough capacity to make the inventory level below the 80% safe max level by reallocating the tanks to the product as shown in Figure 4.12.

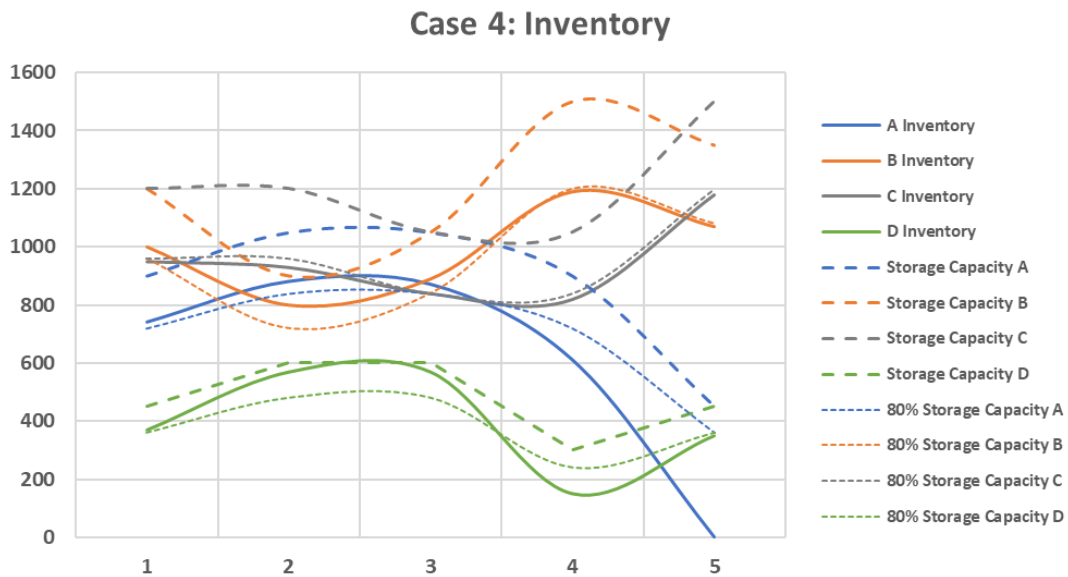


Figure 4.10: Case 4 Inventory

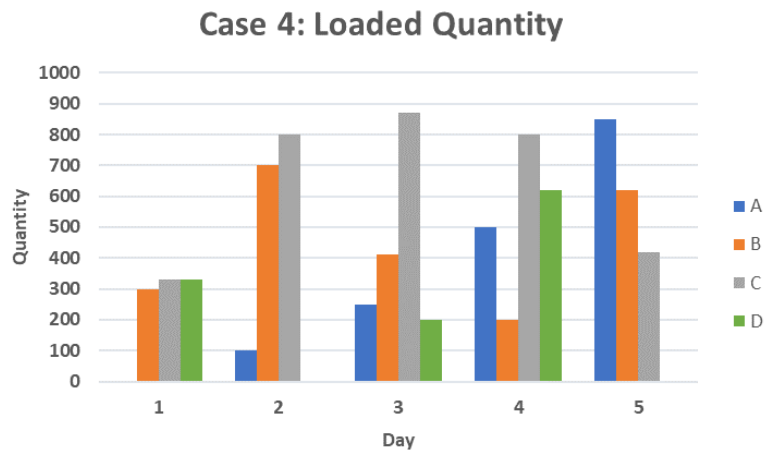
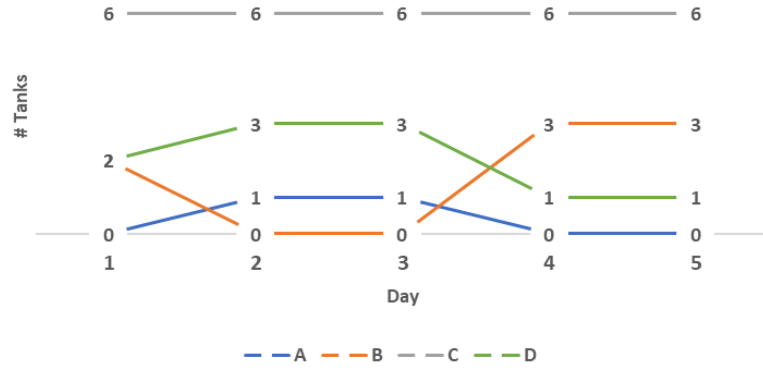
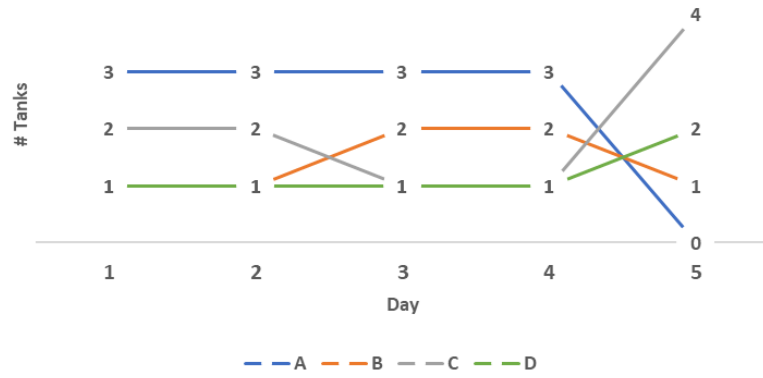


Figure 4.11: Case 4 Loaded Quantity

CASE 4: LA TANKS MANAGEMENT



CASE 4: LB TANKS MANAGEMENT



CASE 4: LC TANKS MANAGEMENT

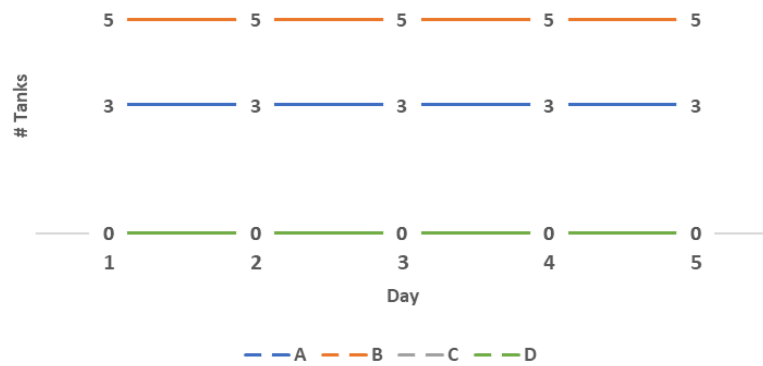


Figure 4.12: Case 4 Tanks Management

4.3 Sensitivity Analysis

Sensitivity analysis focuses on understanding how changes in the model's input parameters can impact the objective function value. By adjusting constraints or coefficients, analysts can determine the robustness of the model. This examination helps in recognizing the stability and reliability of the model under different scenarios, providing valuable insights for decision-making processes. Furthermore, sensitivity analysis can shed light on the capability of the modeled system, by identifying existing bottlenecks. Here a sensitivity analysis is conducted on the proposed model on three main constraints related to assets' availability that are translated to capacities such as storage capacity, loading capacity, and number of daily slots to load the carriers, then evaluating the impact of those capacities on the overall objective function. This model can be used to develop the crude carriers loading plan, depending on the supply and demand, assets' availability impact may behave differently based on the scenario in place. Nevertheless, for the sake of quantifying their impact, the scenario discussed in Case 4 will be used as the base scenario, then three parameters, daily loading capacity $LC_j \forall j$, available tanks at location T_{jkl} for $l = LA$ and the maximum number of carriers allowed at the same day S_j . Table 4.8 shows the change in the selected parameters and the impact on the overall objective function as well as the different metrics that make up the objective function.

For this specific scenario availing more storage capacity leads to the lowest objective

function value, and in contrast, reducing the daily loading capacity resulted in the maximum objective function value as illustrated in Figure 4.13.

Table 4.8: Sensitivity Analysis Result

	Daily Loading Capacity LC_j	Carriers Per day S_j	Number of Tank Available T_{jkl} in LA	Objective Function Value	Max Delayed (Days)	Max Advanced (Days)	Total Deviation (Days)	Inventory Exceeding Soft-Max (Vol.)	Inventory Exceeding Soft-Min (Vol.)	Number of Tanks Service Switch (Tank)
Base Case 4	2,500	5	10	306,264.1	3	3	22	450	2,772.6	10
Sen. Case 1	1,700	5	10	407,370.6	3	4	31	0	4,325.1	6
Sen. Case 2	3,000	5	10	306,264.1	3	3	22	450	2,772.6	10
Sen. Case 3	2,500	6	10	306,264.1	3	3	22	450	2,772.6	10
Sen. Case 4	2,500	3	10	406,154.5	3	4	28	210	2,897.0	11
Sen. Case 5	2,500	5	11	207,633.0	3	2	14	900	3,700.0	8
Sen. Case 6	2,500	5	9	306,570.7	3	3	21	760	2,770.7	10

$$Z = 1000 * Mdel + 99999 * Madv + \sum_{i=1}^n X_i^+ + \sum_{l=1}^m \sum_{k=1}^p \sum_{j=1}^d TSC_{jl}^+ + \sum_{k=1}^p \sum_{j=1}^d r_{jk}^+ + r_{jk}^-$$

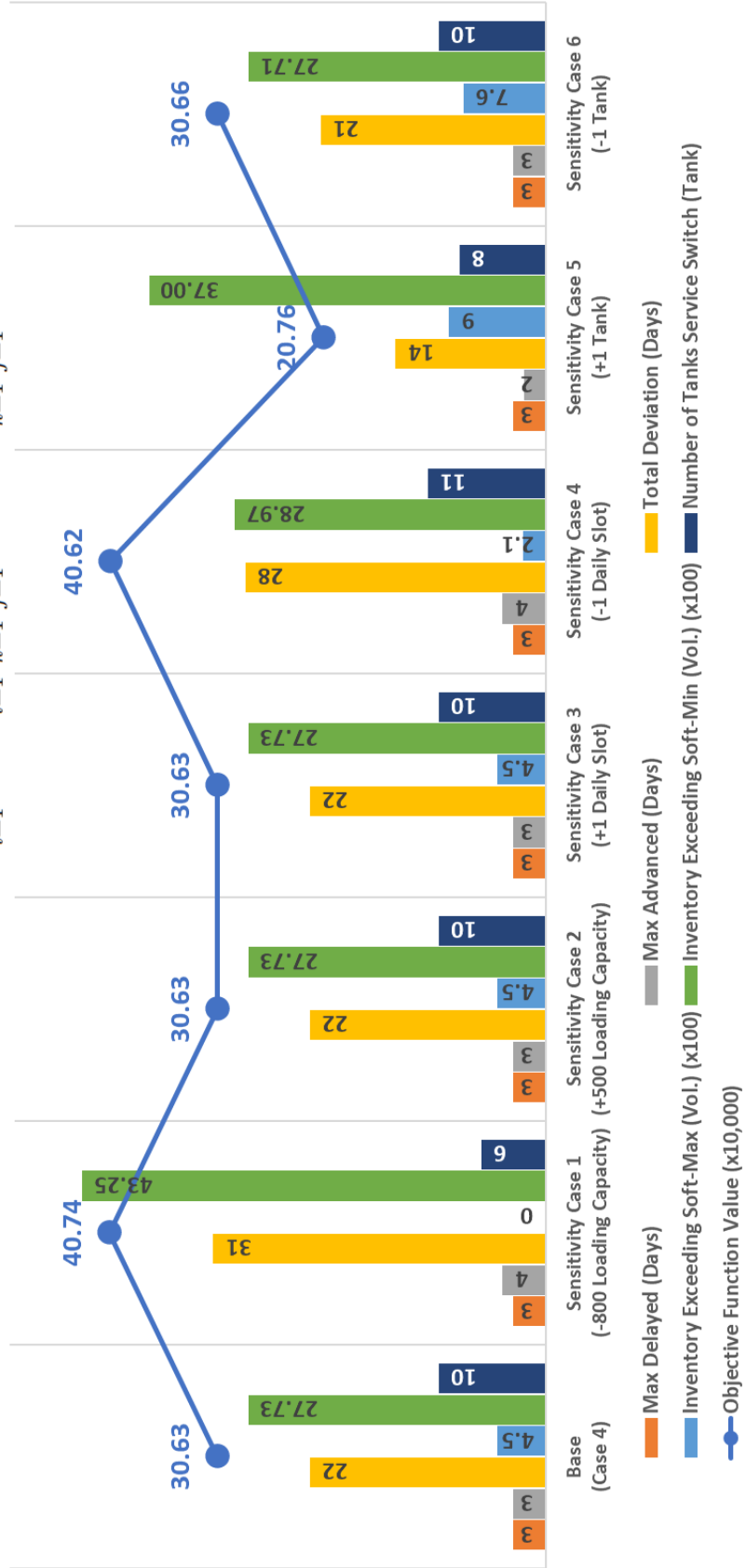


Figure 4.13: Sensitivity Analysis Result

4.4 Full-Scale Problem Result

The mathematical model was modeled in GAMS and solved using Cplex solver. Real-life data was used to experiment and evaluate the model performance that consists of 4 products, 3 tank farms with an aggregated product pool, and a 30-day planning horizon. The solver returned a feasible solution with an optimality gap of 7%, *to the relaxed problem, which has all integer and binary variables as continues*. Nevertheless, the calculated number of days deviated from the requested loading day, matches the linearized absolute value function.

4.4.1 Inventory Profiles

Inventory profiles were generated and illustrated in Figure 4.14 to Figure 4.17. All inventory physical limits were respected, and the model maintained the inventory level to be below the soft max limit of 80% of the capacity. Also, the graphs show how the model allocates tanks for each product at each tank farm, to maintain a minimum loading days deviation.

4.4.2 Loading Day Deviation from Requested Day

The main objective of the model is to minimize the deviation from the requested loading day. The model achieved to schedule 64% of the carriers to load within 2 days of their requested loading day, 10% for 3 to 4 days and 26% more than that,

Figure 4.18 illustrate the absolute deviation distribution and Figure 4.19 illustrates the max, min and average days deference from the requested loading day.

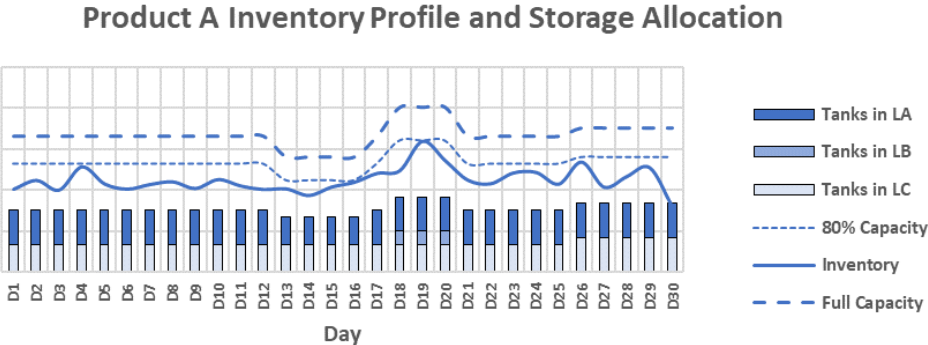


Figure 4.14: Inventory Profile and Storage Allocation for Product A

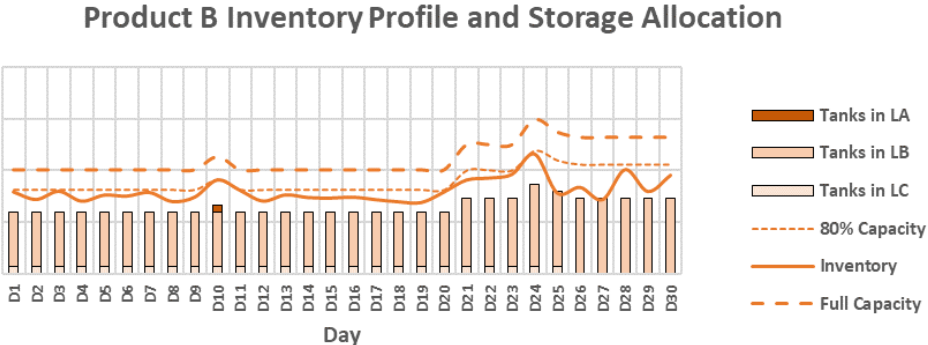


Figure 4.15: Inventory Profile and Storage Allocation for Product B

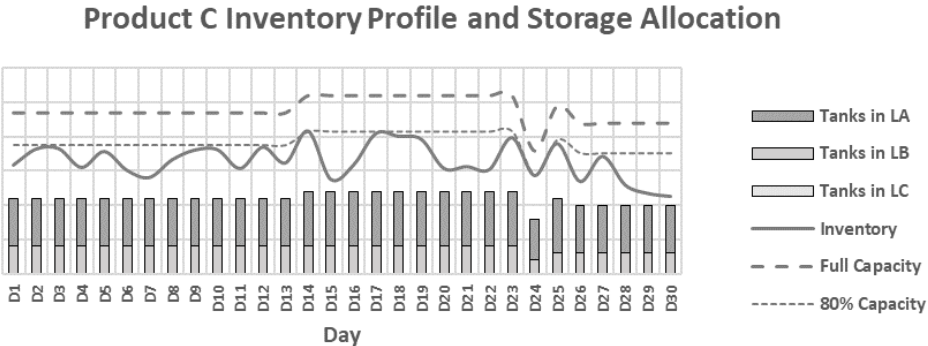


Figure 4.16: Inventory Profile and Storage Allocation for Product C

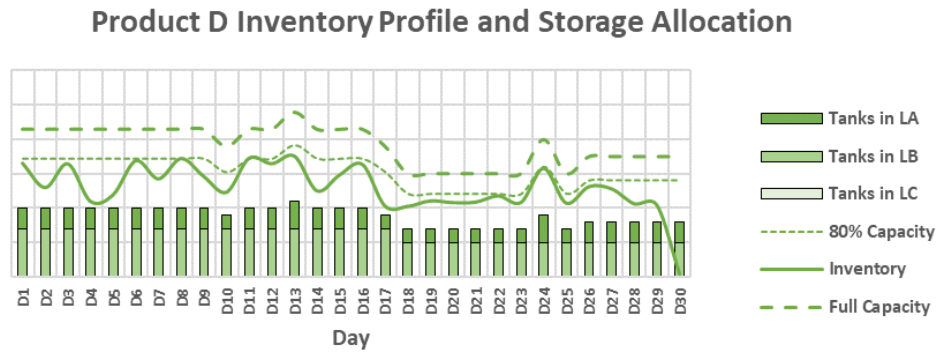


Figure 4.17: Inventory Profile and Storage Allocation for Product D

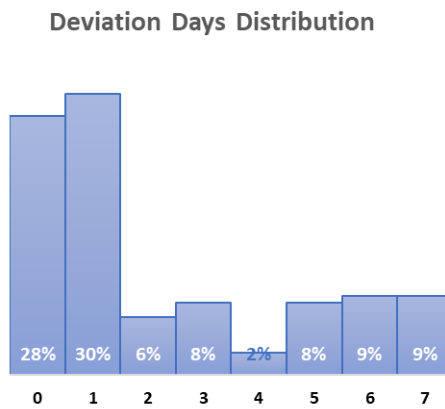


Figure 4.18: Loading Day Absolute Deviation Distribution

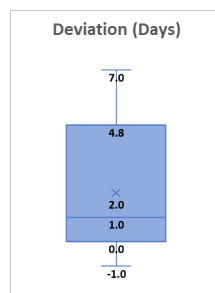


Figure 4.19: Loading Day Deference Box Plot

CHAPTER 5

SOLVING THE PROBLEM AS A MULTI-OBJECTIVE MODEL

The introduced problem has multiple objectives to be solved simultaneously, the objective function formulation as shown in Equation 3.1 uses a single weighted objective to solve the multi-objective optimization model.

$$\begin{aligned} \text{Min } Z = & m^+ * Mdel + m^{++} * Madv + \sum_{i=1}^n X_i^+ * Pr_i \\ & + w * \sum_{l=1}^m \sum_{k=1}^p \sum_{j=1}^d TSC_{jkl}^+ + cr * \sum_{k=1}^p \sum_{j=1}^d r_{jk}^+ + r_{jk}^- \end{aligned} \quad (3.1 \text{ revisited})$$

The objective function can be broken down into multiple objectives and the model can be solved by minimizing each one of them with respect to the others. Also, a lexicographic order is established for the set of objectives to make sure that the best outcome, *that is aligned with the business requirements*, is achieved.

According to the subject matter experts, they wish to minimize the maximum devi-

ation from the customer requested loading date first, then reduce the divination per shipment, with this the first two objectives will be related to the shipment schedule. The remaining objectives are related to the tank farm operations in terms of managing the inventory and the storage capacity for all products. The subject matter experts stated that although it is applicable to change the service for a number of tanks, they would like to keep it to the bare minimum even though that means violating the soft max and soft min inventory constraints. Thus, the third and fourth objectives will be minimizing the number of tanks services switched and minimizing the violation of the soft constraint to exceed the soft limits of inventory respectively.

The lexicographic order for the objectives is as follows:

- Objective 1: Minimizing the maximum days delayed or advanced.

$$Mdel + Madv.$$

- Objective 2: Minimizing the absolute deviation from the requested loading date for each nomination

$$\sum_{i=1}^n X_i^+ * Pr_i.$$

- Objective 3: Minimizing the number of tanks services switched

$$\sum_{l=1}^m \sum_{k=1}^p \sum_{j=1}^d TSC_{jkl}^+$$

- Objective 4: Minimizing the violation of the soft constraint to exceed the soft limits of inventory

$$\sum_{k=1}^p \sum_{j=1}^d (r_{jk}^+ + r_{jk}^-)$$

There are several methods to solve this problem for each objective function such as hierarchical optimization, weighted Tchebycheff procedure, and goal programming.

Here the problem will be solved using the hierarchical optimization method in addition to using the weighted Tchebycheff procedure and then comparing their results with the single weighted objective approach.

5.1 Hierarchical Optimization Model Formulation

The same model formulation, from Equation 3.1 to Equation 3.20, will be used here, with minor modifications. A new set for the objectives will be added, set g , such that there will be one index for each of the four objectives.

g : objective index, $g = 1, 2, 3, 4$ and $g \in Z$

Additionally, the original objective function will be broken into four constraints such that Objective 1 will be solved first then Objective 2 then 3 and lastly Objective 4, and at each stage the value of the previous objective will be introduced in the model as a constraint with maximum deviation of ϵ_g . Each ϵ_g is relative to the units and scale of each objective. The ϵ_g will be determined according to the subject matter expert's opinions.

1. ϵ_1 which is related to the maximum deviation days objective will be zero, since this is the most important objective and it derives the supplier's schedule quality.
2. ϵ_2 which is the additional days of deviation per shipment to be 1.5 to 2 days per shipment.
3. ϵ_3 which is the additional number of tanks to change their service is 1.

Finally, the set of new equations, where $(z_1, \dots, z_4)$ are new variables to the model, will be added to the model is shown in Equation 5.1 to Equation 5.4.

$$z_1 = Mdel + 10 * Madv \quad (5.1)$$

$$z_2 = \sum_{i=1}^n X_i^+ * Pr_i \quad (5.2)$$

$$z_3 = \sum_{l=1}^m \sum_{k=1}^p \sum_{j=1}^d TSC_{jkl}^+ \quad (5.3)$$

$$z_4 = \sum_{k=1}^p \sum_{j=1}^d (r_{jk}^+ + r_{jk}^-) \quad (5.4)$$

And the new objective function formula will be

$$Z = \sum_{g=1}^{zz} po_{gz} * z_g \quad (5.5)$$

where $po_{gz} = 1$ when $gz = g$ and 0 otherwise.

Finally, the model will loop over g as shown in Algorithm 1 and includes z_{g-1}^* which is the minimum achieved value for objective z_{g-1} .

Algorithm 1 Algorithm to loop over objective functions

```

for  $g = 1$  to 4 do
  if  $g \geq 2$  then
    Add constraint  $z_{g-1} \leq z_{g-1}^* + \epsilon_{g-1}$  to the model
  end if
  Solve min  $z_g$  for the model formulated from Equation 3.1 to Equation 3.20
  Next  $g$ 
end for

```

5.1.1 Result

The same problem was used in the multi-objective model that was coded in GAMS and solved using Cplex solver for each objective function. The solver returned a feasible solution with an optimality gap of 6.8% for the first objective, 0% for the second and the third, and less than 1% for the fourth one. Nevertheless, the calculated number of days deviated from the requested loading day, matches the linearized absolute value function.

5.1.1.1 Inventory Profiles

Inventory profiles were generated and illustrated in Figure 5.1 to Figure 5.4. All inventory physical limits were respected, and the model maintained the inventory level to be below the soft max limit of 80% of the capacity. Also, the graphs show how the model allocates tanks for each product at each tank farm.

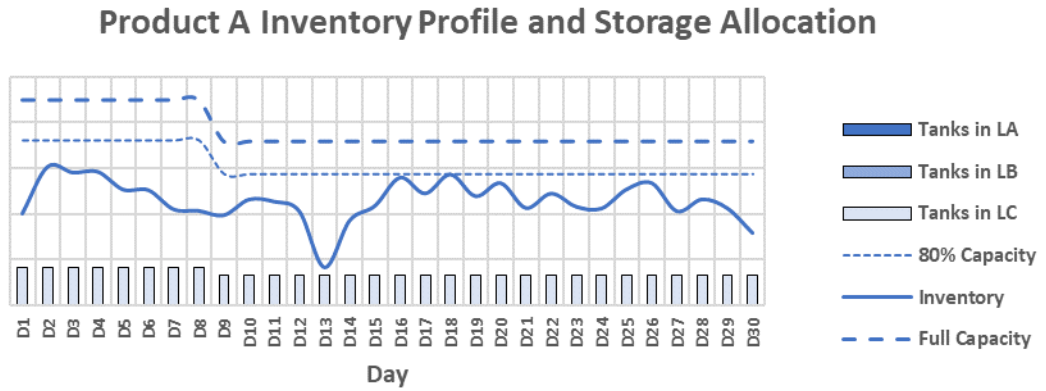


Figure 5.1: Inventory Profile and Storage Allocation for Product A

Product B Inventory Profile and Storage Allocation

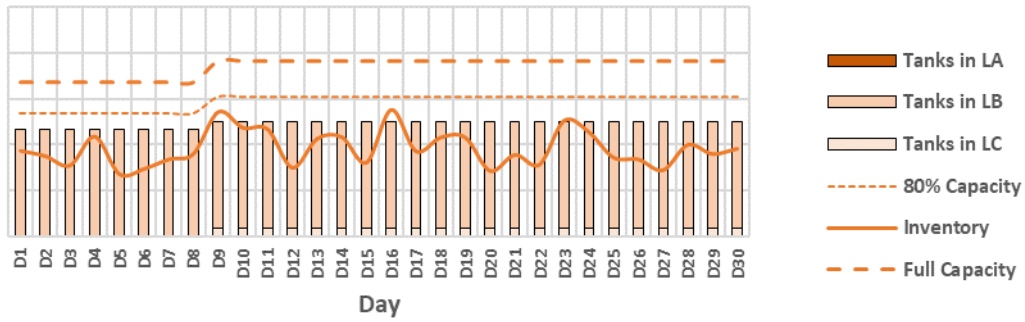


Figure 5.2: Inventory Profile and Storage Allocation for Product B

Product C Inventory Profile and Storage Allocation

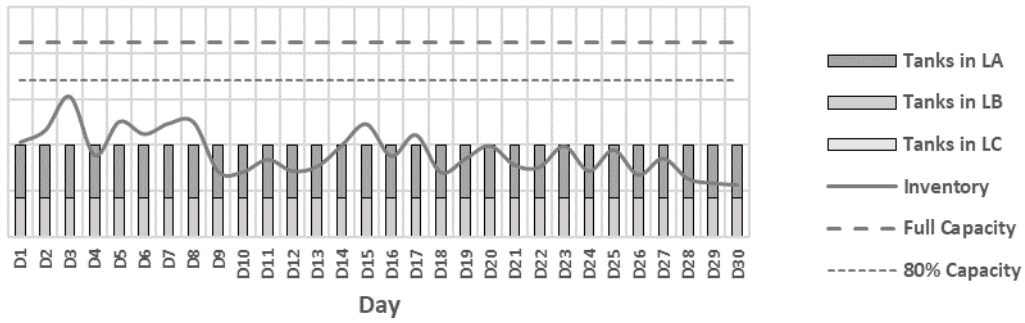


Figure 5.3: Inventory Profile and Storage Allocation for Product C

Product D Inventory Profile and Storage Allocation

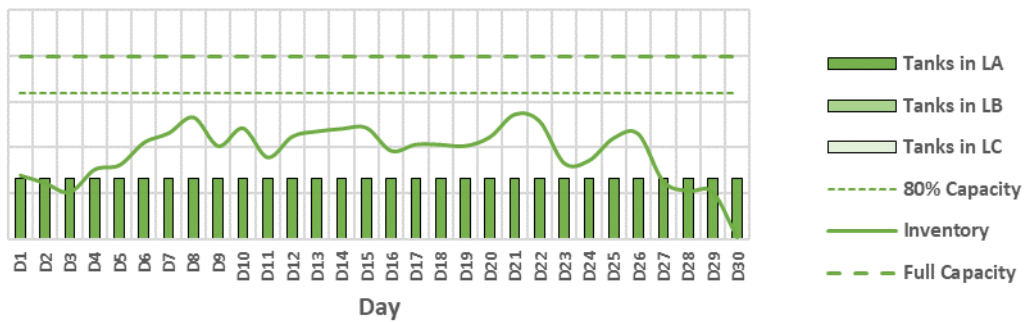


Figure 5.4: Inventory Profile and Storage Allocation for Product D

5.1.1.2 Loading Day Deviation from Requested Day

The multi-objective model achieved to schedule 54% of the carriers to load within 2 days of their requested loading day, 15% for 3 to 4 days and 32% more than that, Figure 5.5 illustrate the absolute deviation distribution and Figure 5.6 illustrates the max, min and average days deference from the requested loading day.

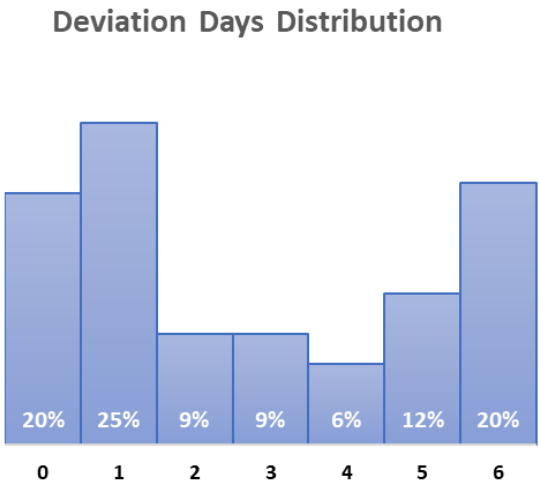


Figure 5.5: Loading Day Absolute Deviation Distribution

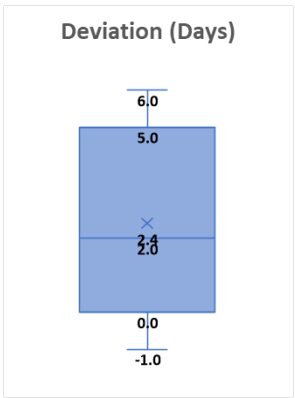


Figure 5.6: Loading Day Deference Box Plot

5.1.2 Objective Functions Value

The purpose of solving the problem using a hierarchical method is to optimize each objective function independently without the influence of others which may have conflicting behaviors. Figure 5.7 shows the behavior of each objective function independently and how conflicting objectives are maintained to be below or at the allowable deviation of ϵ value.

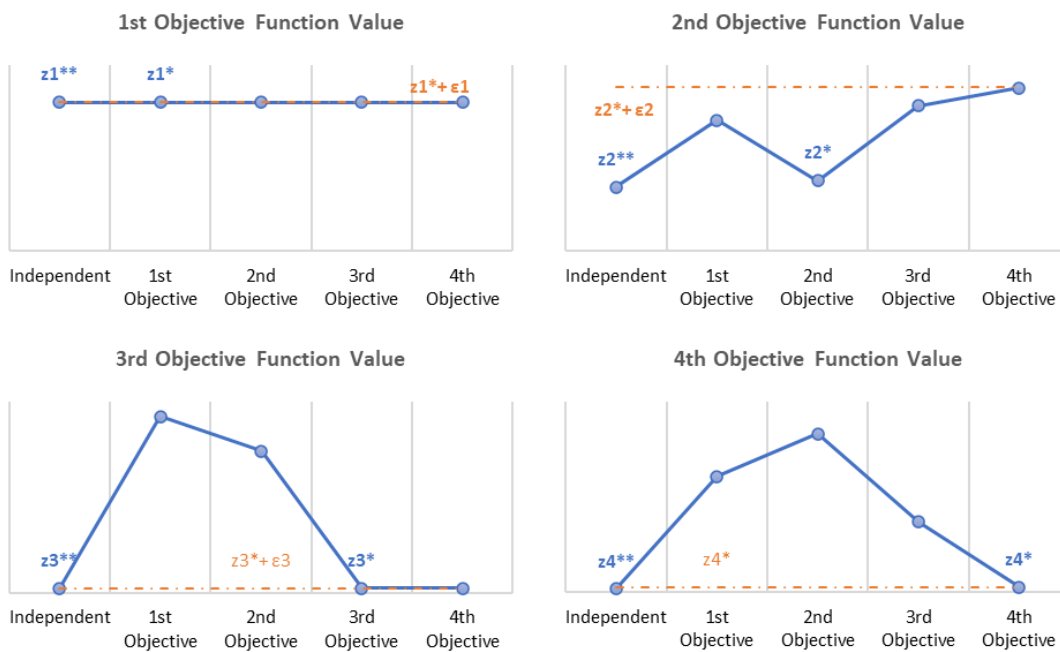


Figure 5.7: Change in Objective Functions

5.2 Weighted Tchebycheff Procedure

Here another approach will be applied to the multi-objective optimization problem, which is the weighted Tchebycheff procedure. The weighted Tchebycheff procedure minimizes the weighted maximum deviation of a feasible solution to a desirable reference point. An alternative feasible solution will be produced by altering the selected weight for each objective, ultimately generating a Pareto feasible region (Helfrich et al., 2023).

The model formulation proposed in this thesis, from Equation 3.1 to Equation 3.20, and the multiple objectives explained in Equation 5.1 to Equation 5.4 will be the basis of the weighted Tchebycheff procedure. Moreover, the best-achieved value for each objective, z_g^{**} , that was produced in section 5.1.2 and shown in Figure 5.7, will be the desired reference point to be achieved. In addition to those, different weights w_g need to be assigned for each objective such that $\sum_{g=1}^{zz} w_g = 1$. This will lead to rewriting the objective function to be as shown in Equation 5.6.

$$Z = \sum_{g=1}^{zz} w_g * (z_g - z_g^{**}) \quad (5.6)$$

5.2.1 Scaling the Objective Function

Since the four objectives in the problem are not homogeneous, *as they do not have the same scale nor unit of measure*, scaling the objective function components to be

between 0 and 1 is necessary to achieve a balanced solver behavior. There are many methods to scale or normalize the data based on their bounds or distribution, such as linear scaling as shown in Equation 5.7, or z-score method illustrated in Equation 5.8.

$$z' = \frac{z - z_{min}}{z_{max} - z_{min}} \quad (5.7)$$

$$z' = \frac{z - \mu}{\sigma} \quad (5.8)$$

However, since there is no clear idea of the absolute bounds nor distribution of every objective, the linear scaling method shown in Equation 5.7 will be used. Where z_{min} value for each objective g will be equal to z_g^{**} and the value of z_{max} will be assumed to be either the maximum value produced by solving each objective independently and capturing the maximum value of objective function g obtained while optimizing other objectives, in similar manner as in subsection 5.1.2, or an appropriate maximum bound based on the specific objective function z_g^{++} .

The scaled objective function will be:

$$Z = \sum_{g=1}^{zz} w_g * \left(\frac{z_g - z_g^{**}}{z_g^{++} - z_g^{**}} \right) \quad (5.9)$$

The objective function introduced in Equation 5.9 is scaled between 0, *when* $z_g = z_g^{**}$, and 1, *when* $z_g = z_g^{++}$. Hence the solver will prioritize minimizing the objective with larger w_g bringing it closer to the minimum achieved value z_g^{**} as intended.

5.2.2 Generating Pareto Feasible Solutions

To produce the Pareto feasible region, the model will be solved multiple times with different w_g at each run. For this problem, the model was solved 5 times and the weights are shown in Table 5.1. Additionally, the relative values for each objective were obtained and shown in Table 5.2. Objective 3 (z_3) was always hitting the minimum value of z_g^{**} , hence it enabled the generation of a single Pareto feasible region showed in Figure 5.8, despite there are 4 objectives to be optimized.

Table 5.1: Weights Values for Each Run

Case	w_1	w_2	w_3	w_4
1 st	0.25	0.25	0.25	0.25
2 nd	0.5	0.3	0.15	0.05
3 rd	0.3	0.5	0.15	0.05
4 th	0.15	0.05	0.5	0.3
5 th	0.05	0.15	0.3	0.5

Table 5.2: Relative Objective's Values

Case	z_1	z_2	z_3	z_4
1 st	0.00	0.11	0.00	0.02
2 nd	0.00	0.07	0.00	0.20
3 rd	0.00	0.05	0.00	0.29
4 th	0.00	0.14	0.00	0.01
5 th	0.21	0.11	0.00	0.00

Where:

z1: Max Deviation (days)

z2: Total Deviation for all carriers (days)

z3: Tanks services Switched (tank)

z4: Inventory soft constraints violations (vol.)

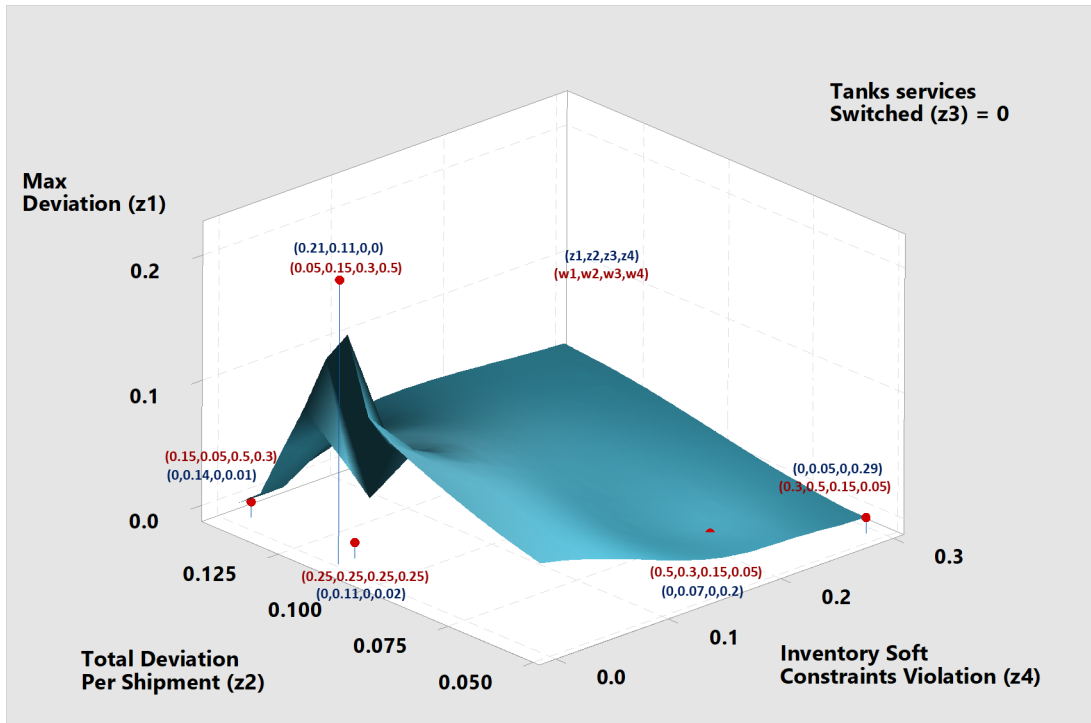


Figure 5.8: Pareto Feasible Solutions Region

5.3 Result Comparison

The results captured from the hierarchical approach and the weighted Tchebycheff procedure, *for Case 1*, were compared with the original approach of the weighted single objective model and it was found that the multi-objective approach in general dominates the weighted single objective for most of the objectives as it shown in Figure 5.9. The weighted sum model dominated the others for Objective 4 due to the large scale of the unit of measure for Objective 4, hence the solver will prioritize it instead of the others.

Furthermore, the weighted Tchebycheff procedure produced a significant improvement compared to the weighted single objective approach in alignment with the business requirements and objectives priority. Adding its flexibility to fine-tune the weights for the objectives to adapt the dynamics of the problem makes it the best approach compared to the other two.

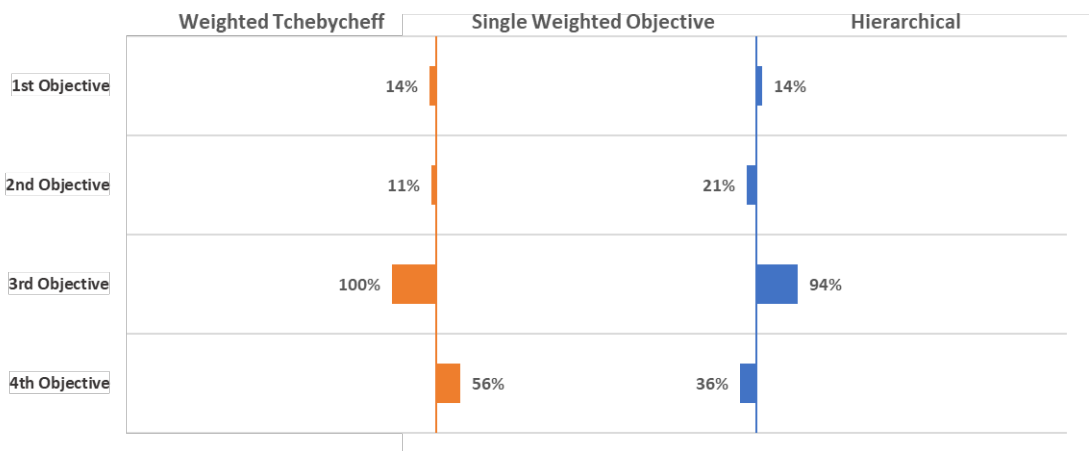


Figure 5.9: Result Comparison

CHAPTER 6

CONCLUSION

The crude oil export scheduling problem from the supplier perspective was not investigated enough in the literature. A problem that is concerned to be a customer centric, with dynamic inventory capacity management, and integrating customers' satisfaction with safe operating levels. The objective of my thesis is to research and investigate the crude oil terminal operations planning and scheduling, for a multi-product dynamic storage capacity problem. In the literature, the majority of the papers are concerned with problems related to vessel routing and berth allocation in the marine supply topics. In this thesis, a novel formulation for Crude oil export scheduling was provided and solved to satisfy business requirements such as: minimizing the maximum deviation from the customers' requested loading date and maintaining a safe level of inventory for all products with the ability to dynamically reallocate storage capacity for available products.

In my thesis, the problem was formulated as a MILP model and was solved using three methods, single weighted objective, hierarchical optimization method, and weighted Tchebycheff procedure as a multi-objective problem. The results captured

from the hierarchical approach and the weighted Tchebycheff procedure were compared with the original approach of the weighted single objective model and it found that the multi-objective approach in general dominates the single weighted objective for most of the objectives. Furthermore, the weighted Tchebycheff procedure produced a significant improvement compared to the weighted single objective approach in alignment with the business requirements and objectives priority. Adding its flexibility to fine-tune the weights for the objectives to adapt the dynamics of the problem makes it the best approach compared to the other two. However, utilizing the weighted Tchebycheff procedure can be time-consuming, especially in obtaining the best available values for each objective and finding the minimum and maximum values to scale the function.

Since the problem was modeled as a MILP, its performance can be enhanced by repressing the time variables to be continuous instead of discrete variables. Additionally, finding an exact solution in a short time is a challenge with this type of model, hence exploring a heuristic approach may reduce the time to find a near-optimal solution. Finally, integrating the whole crude oil supply from producing facilities to customers can be researched to produce a holistic model that can produce production and export plans to minimize inventory-related costs and maintain high service levels.

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