

**IMPROVING PETROCHEMICAL
SUPPLY CHAIN SUSTAINABILITY:
AN OPTIMIZATION APPROACH FOR
PRODUCTION PLANNING AND
MAINTENANCE SCHEDULING**

BY

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Dedication
To my beloved
Family]

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LIST OF ABBREVIATIONS

ACE : Acetylenes

BTD : Butadiene

BTN : Butene-1

C₂ : Ethane

C₃ : Propane

C₄ : Butane

C₅+ or NGL : Natural Gas Liquid

HCSP : Hydrocarbon supply chain

MMCSF: Million Standard Cubic Feet

MTBE : Methyl Tert-Butyl Ether

Off-Spec : Off-Specification

OLF : Olefins/Double bonds

PCSC : Petrochemical supply chain

SC : Supply Chain

TAM : Turnaround maintenance

Raff : Raffinate

Raff-1 : Raffinate-1

Raff-2 : Raffinate-2

Raff-3 : Raffinate-3

|

ABSTRACT

Full Name : Nabeel Saad Alanbar
Thesis Title : Improving Petrochemical Supply Chain Sustainability: An Optimization Approach for Production Planning and Maintenance Scheduling
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Petrochemical supply chain (PCSC) optimization involves complex production planning, inventory management, and sustainability efforts to maximize profit. It integrates these components, requiring advanced data analytics and a holistic optimization modeling approach. Achieving this optimization is crucial in the context of shifting to sustainable practices and reducing environmental footprints, all amid evolving market dynamics and regulations. The model aims to maximize overall supply chain profit while minimizing environmental impact and managing both feedforward and reverse logistics. This integrated approach optimizes production planning, inventory control, and logistics network management. Its practicality is demonstrated through implementation in a C₄ supply chain from Saudi Arabia, where the system is optimized under specific policies. Integrating operation and maintenance activities along the PCSC is crucial due to its significant influence on the continuity of production and its consequences on satisfying customer demand. Turnaround Maintenance (TAM) is a periodic process involving plant shutdowns for inspections, repairs, preventive maintenance, and time-based overhauls. These shutdown periods typically range from three to four weeks, and prolonging them is costly, necessitating effective planning. This research aims to develop a comprehensive mathematical programming model to coordinate and plan TAM for the C₄ supply chain

system with production planning, inventory control, logistics management, and sustainability aspects in an integrated framework. The developed model optimally plans TAM for several plants, ensuring efficient maintenance scheduling. A sensitivity analysis is performed to investigate the impact of key factors on the findings obtained.

ملخص الرسالة

الاسم الكامل: نبيل سعد العنبر

عنوان الرسالة: تحسين استدامة سلسلة توريد البتروكيماويات: نهج التحسين لتخطيط الإنتاج وجدولة الصيانة

التخصص: الهندسة الصناعية والنظم

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يتضمن تحسين سلسلة توريد البتروكيماويات تخطيطاً معقداً للإنتاج وإدارة المخزون وجهود الاستدامة لتحقيق أقصى قدر من الربح. إنه يدمج هذه المكونات، ويتطلب تحليلات بيانات متقدمة ونهجاً شاملاً. يعد تحقيق هذا التحسين أمراً بالغ الأهمية في سياق التحول إلى ممارسات مستدامة والحد من البصمات البيئية، كل ذلك وسط ديناميكيات السوق واللوائح المتطورة. يهدف النموذج إلى تعظيم ربح سلسلة التوريد الإجمالية مع تقليل التأثير البيئي، مع مراعاة كل من اللوجستيات الأمامية والعكسية. يعمل هذا النهج المتكامل على تحسين تخطيط الإنتاج والتحكم الاستراتيجي في المخزون وإدارة شبكة اللوجستيات. يتم إثبات عمليته من خلال التنفيذ في سلسلة توريد C4 من المملكة العربية السعودية، حيث يتم تحسين النظام بموجب سياسات محددة. يعد دمج أنشطة التشغيل والصيانة على طول سلسلة توريد البتروكيماويات أمراً بالغ الأهمية نظراً لتأثيره الكبير على الاقتصاد العالمي. تعد الصيانة الدورية عملية دورية تتضمن إغلاق المصنع للتفتيش، والإصلاح والصيانة الوقائية والإصلاحات. تتراوح فترات الإغلاق هذه عادةً من ثلاثة إلى أربعة أسابيع، وإطالة أمدتها أمر مكلف، مما يتطلب التخطيط الفعال. يهدف هذا البحث إلى تطوير نموذج برمجة رياضي لتنسيق وتخطيط إدارة الأصول الثابتة لنظام سلسلة التوريد C4 ضمن إطار متكامل. يخطط النموذج المتطور بشكل مثالي لإدارة الأصول الثابتة للعديد من المصانع، مما يضمن جدولة صيانة فعالة. سيتم إجراء تحليل الحساسية لدراسة تأثير المعلمات الحرجة على النتائج التي تم الحصول عليها.

CHAPTER 1

INTRODUCTION

1.1 Introduction to the PCSC

The petrochemical industry stands as a cornerstone of modern society, serving as a lifeblood for various sectors ranging from manufacturing to transportation. Amidst its critical role, the intricacies of managing the petrochemical supply chain (PCSC) pose a myriad of challenges that demand nuanced solutions (Alfares, 2023; Elsaghier, 2017). This research delves into the complexities inherent in PCSC management, exploring the intricate interplay of factors such as feedforward and reverse logistics, production planning, inventory control, and emissions reduction.

In recent years, the emergence of feedforward and reverse logistics has reshaped conventional supply chain paradigms, introducing both opportunities and complexities. While feedforward logistics streamlines the flow of raw materials and products toward production and distribution channels, reverse logistics addresses the challenges of handling returns, waste, and recycling, a domain particularly pertinent in the petrochemical industry where sustainability concerns are paramount (Dyckhoff et al., 2013).

Navigating these logistics intricacies is further compounded by the multifaceted difficulties inherent in the PCSC. From volatile market dynamics to geopolitical tensions and

regulatory constraints, stakeholders face a landscape rife with uncertainty (Sahebi et al., 2014). Moreover, the industry grapples with the imperative of balancing production planning with inventory control while concurrently mitigating environmental impacts, particularly in terms of emissions reduction, an endeavor that necessitates innovative strategies and technologies (Ratnakar et al., 2021; Riera et al., 2023).

This review examined recent research on optimizing petrochemical supply chain management, encompassing production planning, inventory management, footprint reduction, and profit maximization. The studies explored various methodologies and objectives, highlighting the increasing integration of environmental considerations.

Several studies addressed production planning optimization. Li et al. (2024) proposed a framework integrating refinery, ethylene plant, and aromatics complex production, demonstrating significant profit improvement. Jiao et al. (2022) investigated the integration of production and transportation, finding reduced costs and emissions. Kwon et al. (2022) presented a decision-supporting platform for production planning, achieving higher profits with paper trading optimization.

Environmental impact is gaining prominence in supply chain optimization. Zheng et al. (2024) designed a green petroleum supply chain network considering multi-mode transportation and CO₂ emissions. Abdussalam et al. (2021) developed a tool based on data from the oil and gas sector. Their model achieved significant carbon emission reduction.

Attia et al. (2019) presented a multi-objective optimization model for crude oil and natural gas by-products, considering environmental impact alongside cost-effectiveness.

Multiple studies explored cost minimization through optimization models. Freen et al. (2023) proposed linear programming models to minimize refineries, depots, and transportation costs. Arya et al. (2023) compared optimization models for fuel consumption minimization in a gas pipeline network. Abdussalam (2021) presented a model for planning and optimizing petroleum supply chains from a country-level perspective, considering economic aspects. Homchalee and Sessomboon (2014) developed a model to minimize total costs in the ethanol supply chain. Rijn (2023) addressed uncertainties in the petrochemical supply chain by incorporating robust optimization models into aggregate production planning. Ebrahimi and Bagheri (2022) focused on optimizing resource supply chains in developing countries, addressing disruptions, and maximizing profit. Their study emphasized the need to consider uncertainty in future research.

Several studies identified opportunities for future research. Li et al. (2024) called for the development of complex and accurate models due to increasing operation costs and stringent environmental regulations. Qiu et al. (2023) suggested considering the uncertainty of oil demand and production and refining pipeline pricing strategies. Tong et al. (2023) highlighted the need for multi-objective models considering economic, environmental, and social sustainability. Rijn (2023) recommended refining the adjustable robust optimization model and exploring tailored statistical forecasting methods. Kwon et al. (2022) suggested developing more reliable decision models. Ebrahimi and Bagheri

(2022) emphasized incorporating uncertainty, heuristic algorithms, and discount rates into future research.

1.2 The Role of Maintenance

Few researchers have looked into how to make operational planning work best when plants are available and fully loaded, but this is a reasonable assumption. When making operating plans, it is imperative to consider disruptions or unexpected plant shutdowns. In reality, periodic maintenance, shutdowns, and other reasons may cause plants to be entirely or partially unavailable. As a result, production capacities will decline or cease altogether. Planned breakdowns can be avoided, and production rates can be raised by giving plants frequent and routine maintenance to keep them healthy and operating at maximum capacity. The device's lifespan is extended, and unexpected breakdowns are decreased through maintenance. As a result, operation planning models must consider the repair schedule and be more realistic. Maintenance tasks should be carried out while demand is low in order to avoid significant production losses and ultimately meet customer expectations. Additionally, before choosing to carry out maintenance tasks, links between upstream and downstream factories must be taken into account, particularly in intricate networks like the petrochemical supply chain.

Particularly in the supply chain environment, the integration of operation and maintenance activities has not received enough attention. Production planning and maintenance scheduling have never been addressed concurrently in the PCSC. This part will, therefore, examine integrated models in the field of inventory control as well as models for petroleum

plant maintenance scheduling. Operation and maintenance schedules have been handled separately in the PCSC.

Ghaithan et al. (2017) developed a multi-objective model for the hydrocarbon supply chain operational planning based on the presumption of the entities accessible during the planning period. The maintenance schedule of individual petroleum network entities, such as refinery plants, has received little attention in research.

Alkhamis & Yellen, (1995) created a Mixed Integer Linear Programming (MILP) model to help a refinery facility schedule preventative maintenance. The suggested approach seeks to optimize unit use level while meeting maintenance constraints. Recognizing the unpredictability of maintenance time, Awad & Ertem (2017) created a stochastic model to arrange preventative maintenance for an oil refinery facility. The model aims to fulfill the multiple-skill-level maintenance personnel and budget constraints while reducing the adjusted tardiness times. Petroleum refineries depend on crude oil planning and scheduling as the possible financial gains are rather important (Xu et al., 2017). Crude oil scheduling operations are somewhat sensitive to changes brought about by different uncertainties. This work presents a novel proactive scheduling strategy concurrently spanning crude unloading, transfer, and processing (CUTP). The CUTP scheduling methodology is designed to optimize the total profit with respect to a variety of inventory, operation, transportation, and production constraints, all while preserving the refinery's standard operating conditions in the face of possible crude shipping delays. A combined feasibility index has been constructed and included in the proposed continuous-time mixed-integer

non-linear programming scheduling model, which the global solver of ANTIGONE solves, to assess shipping delay uncertainties. Furthermore, the link between the minimal flexibility criterion and the overall profit is considered. Xu et al (2017). have clearly shown the effectiveness of this research, who created a proactive scheduling system to keep refinery facilities open amid crude shipment delay uncertainty. A mixed-integer non-linear programming (MINLP) model has been developed to improve the refinery facility's crude unloading, transporting, and processing processes. Recently, (Qu et al., 2019) extended the Xu et al (2017). work by integrating proactive and reactive scheduling.

Ghaithan (2020) created a maintenance and operating model encompassing the whole gas and oil supply chain. The model included the supply chain plants' operating plans and maintenance schedules, which were cooperatively produced. An integrated model was compared to one that did not include operation and maintenance tasks.

In conclusion, the PCSC optimization literature is evolving rapidly, emphasizing sustainability alongside traditional cost reduction objectives. As environmental regulations tighten and operational complexities increase, future research is expected to focus on developing models that integrate production planning, transportation, and environmental considerations.

1.3 Structure of the Thesis

The remainder of this thesis is organized as follows: Chapter 2 provides a comprehensive literature review, highlighting key research gaps and methodologies related to

petrochemical supply chain optimization and maintenance scheduling. Chapter 3 introduces the C₄ petrochemical supply chain, explaining its components, processes, and the problem statement. Chapter 4 develops the mathematical optimization model, detailing its sets, variables, constraints, and objectives while integrating production planning and maintenance scheduling. Chapter 5 presents the case study, including data collection, assumptions, and system parameters for model implementation. Chapter 6 analyzes the results, comparing maintenance scenarios and conducting sensitivity analysis to evaluate system performance. Finally, Chapter 7 concludes the study by summarizing the findings, contributions, and limitations while suggesting future research directions.

1.4 Thesis Objectives

The main objectives for the thesis on optimizing the petrochemical supply chain system are outlined as follows:

- Develop and implement a mathematical model to optimize the flow of materials through the C₄ system.
- Maximize the profitability of the C₄ supply chain by optimizing operational and logistical efficiencies.
- Reduce environmental footprint and comply with regulatory standards.
- Ensure the supply chain is reliable by meeting customer and market demand with minimum excess or shortage.
- Formulate a mathematical model for operations, inventory, logistics, and maintenance planning.

1.5 Methodology

a. Problem Definition and Scope

Clearly define the optimization problem, including its objectives (e.g., minimizing costs, maximizing output) and the scope and constraints. Establish what needs to be achieved and identify specific conditions that must be considered.

b. Data Collection and Preparation

Gather relevant data, including historical records, operational parameters, and economic metrics. Ensure the data is cleaned and verified for accuracy, removing irrelevant or erroneous information to maintain model reliability.

c. Model Formulation

Structure the problem as a Mixed-Integer Linear Programming (MILP) model. The MILP integrates production planning, inventory control, and maintenance scheduling, combining binary and continuous variables with linear constraints to achieve computational efficiency and robust solutions.

d. Solver Selection and Configuration

Select an appropriate solver based on the problem type and complexity. The COIN-OR Branch-and-Bound method was chosen for its efficiency in solving MILP problems. Configure the solver with specific settings, such as tolerance levels, maximum iterations, and initial conditions, to guide the optimization process.

e. Model Execution

Run the model using the configured solver, monitoring its performance to ensure convergence. Address any issues, such as non-convergence or high computation times, by adjusting configurations or refining constraints.

f. Result Analysis

Analyze the output to validate the solution. This includes reviewing decision variable values, assessing the objective function, and conducting sensitivity analyses to evaluate the impact of parameter variations. Ensure the solution aligns with constraints and meets the defined objectives.

CHAPTER 2 |

LITERATURE REVIEW

2.1 Gaps in PCSC Optimization

The integration of PCSC optimization and maintenance scheduling in HCSC has not been sufficiently investigated; no work has taken into account an integrated model. The following section investigates state-of-the-art maintenance scheduling models for petroleum facilities, as well as integrated models for inventory management and operations planning in uncertain environments. Table 1 highlights key research contributions across industrial and operational domains.

The literature reflects a diverse approach to decision-making and modeling methodologies across various segments, decision levels, and analytical frameworks. Several studies focus on comprehensive systems, addressing upstream, midstream, and downstream segments. For instance, Li et al. (2024) and Jiao et al. (2022) provided an integrated perspective on these systems, while others, like Homchalee & Sessomboon (2014), concentrated on midstream operations.

Regarding decision-making, a significant portion of the research spans strategic, tactical, and operational levels. Authors like Attia et al. (2019) and Freen et al. (2023) adopted a holistic approach that encompasses all levels, whereas some studies such as Homchalee &

Sessomboon (2014), focused primarily on operational decision-making, emphasizing immediate, practical outcomes.

Analytical methods employed in the literature are predominantly deterministic or stochastic. Abdussalam et al. (2021) applied deterministic approaches, ensuring precision under known conditions. Conversely, Arya et al. (2023) integrated stochastic methods to handle uncertainties, reflecting the complexity of real-world scenarios.

Regarding modeling techniques, many studies rely on linear methods, as well as mixed-integer linear programming (MILP) and linear programming (LP). These approaches, seen in works like those of Zheng et al. (2024) and Attia et al. (2019), offered structured and computationally efficient solutions. Non-linear models, such as those used by Ebrahimi & Bagheri (2022) and Alkhamis & Yellen (1995), addressed problems requiring greater flexibility, employing methods like non-linear programming (NPL) and mixed-integer non-linear programming (MINLP).

Incorporating environmental considerations has gained prominence in recent research, with authors such as Kwon et al. (2022) and Zheng et al. (2024) emphasizing sustainable practices. Earlier studies, such as Alkhamis & Yellen (1995), often overlooked these aspects, reflecting a historical trend less focused on sustainability.

2.2 Maintenance Scheduling in PCSC

The integration of PCSC optimization and maintenance scheduling in HCSC is another area of focus, though less frequently addressed. Table 2 highlights key research contributions across industrial and operational domains. In Maintenance Scheduling, Alkhamis and Yellen (1995) introduced integer programming for refinery maintenance scheduling, while Attia (2025) developed integrated maintenance scheduling for production, inventory, and transportation in OGSC. Antomarioni et al. (2019) presented data-driven maintenance policies, and Bertolini et al. (2009) proposed risk-based inspection procedures. Aissani et al. (2009) applied multi-agent systems for dynamic scheduling. Amaran et al. (2015) focused on long-term turnaround maintenance planning in chemical plants, highlighting its benefits in minimizing downtime and enhancing operational efficiency. Similarly, Ghaithan (2020) emphasized turnaround maintenance during low-demand periods to reduce disruptions. Awad and Ertem (2017) modeled preventive maintenance under uncertainty.

In Production and Maintenance, Cassady and Kutanoglu (2003) integrated preventive maintenance and production scheduling to minimize delays. Aghezzaf et al. (2007) developed hybrid models, Yalaoui et al. (2011) focused on multi-machine scheduling, and Xu et al. (2017) addressed crude oil shipping delays through proactive scheduling.

For Oil and Gas Supply Chain Logistics, Dempster et al. (2000) applied stochastic programming to logistics. Goel and Grossmann (2004) addressed offshore gas field planning under uncertainty, while Al-Othman et al. (2008) tackled pricing and demand

uncertainties. Fernandes et al. (2015) explored oil market uncertainties, Lima et al. (2018) studied tactical planning under uncertainty, and Zhang et al. (2019) combined MILP and Monte Carlo sampling.

In Operations Research Techniques, Mendez et al. (2006) used MILP for refinery scheduling, Göthe-Lundgren et al. (2002) optimized production scheduling and Pudasaini (2021) analyzed transportation costs under uncertainty. Finally, Uncertainty in Scheduling includes Li et al. (2004) addressing raw material uncertainties and MirHassani and Noori (2011) tackling investment planning. These contributions demonstrate the importance of maintenance and operational optimization under complex conditions.

2.2.1 Importance of Partial maintenance

Partial maintenance is an emerging and strategic approach within industrial maintenance planning that allows the continued operation of unaffected units while specific units undergo maintenance or shutdowns due to failures. Unlike total shutdowns, which halt the entire facility, partial maintenance isolates affected components to minimize disruptions and maintain partial production. The benefits of this approach shine through in integrated systems, such as chemical and petrochemical plants, where extended downtime can result in significant operational and economic losses.

Chong and Swartz (2013) emphasized the importance of buffer tanks and bypass streams in managing material flow during partial shutdowns. These mechanisms enable facilities to stabilize production rates, maintain buffer inventories, and reroute materials effectively,

ensuring operational continuity even during maintenance activities. Optimization techniques, such as Mixed-Integer Dynamic Optimization (MIDO), facilitate the implementation of partial maintenance strategies by balancing economic objectives, operational constraints, and restoration times.

Moreover, advanced frameworks, including multitiered optimization and Model Predictive Control (MPC), have dynamically adjusted operations during partial maintenance. These methods enable real-time decision-making to address uncertainties or disturbances, such as unforeseen equipment failures or deviations from expected performance.

2.2.1.1 Olefin Plants Segments

Olefin plants play a critical role in the petrochemical industry as some of the most profitable facilities, producing high-demand products such as ethylene and propylene. These plants are integral to the global chemical supply chain, providing essential feedstocks for a wide range of industrial and consumer goods. Ghadyanlou and Vatani (2015) highlighted that the operational efficiency of these plants, particularly during startups and shutdowns, directly impacts their profitability and environmental footprint. The authors underscore the potential of improving sustainability and economic performance in olefin plants through technologies.

A typical olefin plant operates through several key sections, as shown in Figure 1, each dedicated to specific production process phases. The Feed and Furnace Section initiates the

process by heating and cracking feedstocks such as naphtha or ethane into smaller hydrocarbons, forming the raw materials for downstream processing. The Quench and Fractionation Section follows, where the cracked gases are rapidly cooled to stabilize them and then separated into specific streams based on their boiling points. The cracked gases are compressed in the Compressor and Condensate Section, and condensates are removed to prepare the materials for further purification. Finally, the Hydrocarbon Separation Section completes the process by separating hydrocarbons into desired products like ethylene and propylene through advanced techniques such as distillation. This systematic division ensures efficient handling of materials, optimized production, and high-quality outputs, as highlighted by Ghadyanlou and Vatani (2015).

In conclusion, significant efforts have been made to optimize hydrocarbon supply chains (HCSC), although the majority of models are mostly oil- or gas-centric and concentrate on singular goals. This study intends to address this gap by providing a deterministic MILP optimization model for tactical decision-making and building a mathematical programming model to coordinate and plan turnaround maintenance (TAM) for the C₄ supply chain system within an integrated framework. The model ensures optimal TAM scheduling across multiple plants, improving overall efficiency.

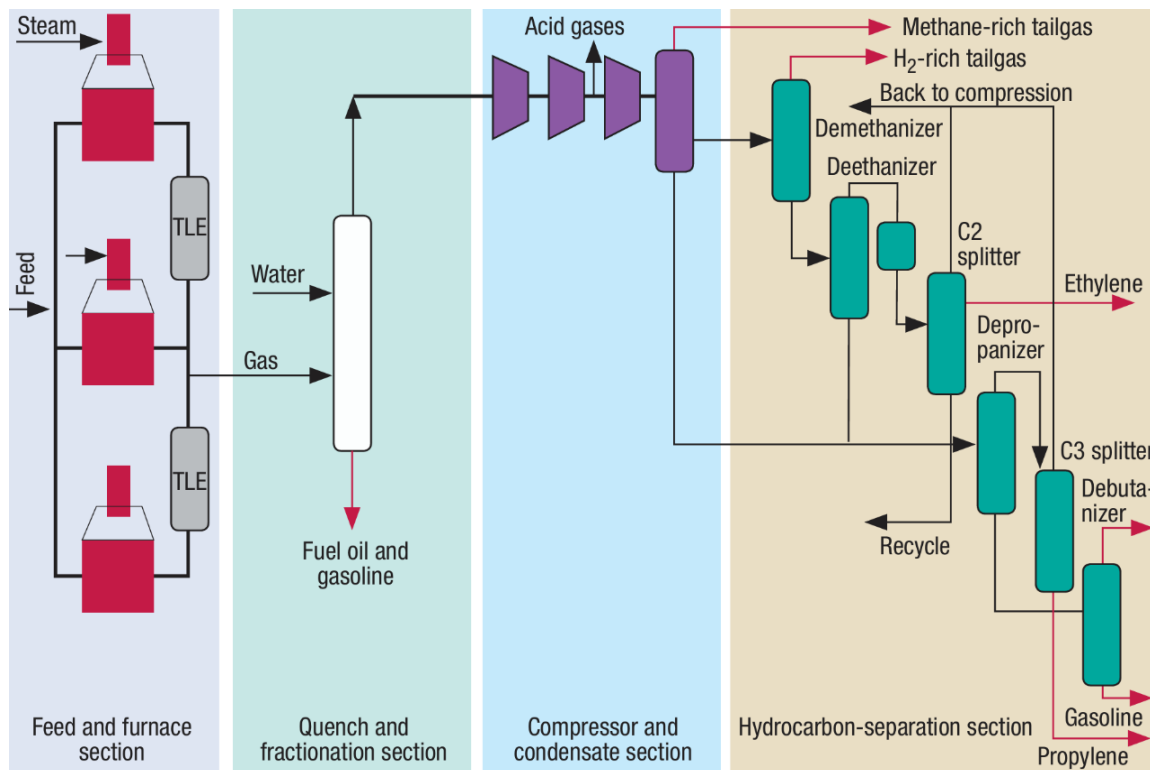


Figure 1 A typical flowsheet for an olefin plant Ghadyanlou and Vatani (2015).

2.3 Research Gap

This research dives into covering the research opportunity highlighted by the literature review in the PCSC, aiming to optimize production and minimize environmental impact. It proposes an optimization model integrating reverse logistics, production planning, and inventory control. This comprehensive approach tackles the challenge of managing excess production while minimizing the environmentally hazardous practice of flaring. By incorporating reverse logistics, this thesis explores how to efficiently re-introduce excess raw materials or productions back into the production cycle, potentially reducing reliance on fresh supplies. The optimized production plan, informed by robust inventory control, would ensure efficient use of raw materials and minimize waste generation. The ultimate goal is to achieve a delicate balance: reducing gas emissions through minimized flaring

and optimizing total costs. This translates to a win-win scenario for both the environment and the company's bottom line, potentially leading to significant profit maximization through cost reduction and potentially increased efficiency.

Furthermore, the literature study indicated that several research studies have examined the amalgamation of operation and maintenance operations inside a singular entity across various domains and applications, including inventory management. To the author's knowledge, no literature exists that integrates operation planning, inventory control, and logistics management with maintenance scheduling for PCSC.

Table 1 Summary of the reviewed papers on HCSC optimization

Author	Segments	Decision Levels	Analytical Approach	Modeling Approach	Linear Models	Non-linear Models	Environmental Aspects	Maintenance
	Up stream : US	Strategic : S	Deterministic : D	Linear : L	Linear programming : LP	Non-Linear programming : NPL		
	Mid stream : MS	Tactical : T	Stochastic : S	Non-linear : NL	Mix integer Linear programming : MILP	Mix integer Non-Linear programming : MINLP		
	Down stream : DS	Operational : O						
Li et al. (2024)	MS,DS	S,T	D	L	LP			
Jiao et al. (2022)	US,DS,MS	T,O	D	L	MILP		E	
Kwon et al. (2022)	MS,DS	O	D	L	MILP			
Zheng et al. (2024)	MS,DS	S,O	D	L	MILP		E	
Abdussalam et al. (2021)	MS,DS	O	S	L	MILP		E	
Attia et al. (2019)	US,DS,MS	S,O	D	NL		NPL	E	
Freen et al. (2023)	DS	T,O	D	L	LP			
Arya et al. (2023)	MS	T,O	D	L	LP		E	
Homchalee & Sessomboon (2014)	US,DS,MS	S,T,O	D	L	LP			
Rijn (2023)	MS,DS	S,O	S	L	LP			
Ebrahimi & Bagheri (2022)	MS,DS	S,O	S	NL		MINLP		

Ghaithan et al. (2017)	US,DS,MS	S,O	D	NL		NLP	E	
Alkhamis & Yellen (1995)	MS	T,O	S	L	LP			
Awad & Ertem (2017)	MS,DS	T,O	S	L	LP			
Xu et al. (2017)	MS	T,O	D	L	LP			
Qu et al. (2019)	MS,DS	T,O	D	NL		NLP		
Our Study	MS	T	D	L	MILP		E	M

Table 2 Summary of the reviewed papers on maintenance

	Maintenance Type				Category				
Authors	TA M	CB M	RB M	TB M	Maintenanc e Scheduling	Production and Maintenan ce	OGSC Logistics	Operations Research Techniques	Uncertainty in Scheduling
Alkhamis and Yellen (1995)	✓				✓				
Antomarioni et al. (2019)		✓			✓				
Bertolini et al. (2009)			✓		✓				
Aissani et al. (2009)		✓			✓				
Amaran et al. (2015)	✓	✓			✓				
Awad and Ertem (2017)		✓			✓				
Ghaithan (2020)	✓				✓				
Attia (2025)	✓				✓				
Cassady and Kutanoglu (2003)				✓		✓			
Aghezzaf et al. (2007)				✓		✓			
Yalaoui et al. (2011)				✓		✓			
Xu et al. (2017)		✓		✓		✓			
Dempster et al. (2000)			✓				✓		
Goel and Grossmann (2004)			✓				✓		
Al-Othman et al. (2008)			✓				✓		
Fernandes et al. (2015)			✓				✓		

Lima et al. (2018)			✓				✓		
Zhang et al. (2019)			✓				✓		
Alnaqbi et al. (2023)			✓				✓		
Attia (2021)			✓				✓		
Mendez et al. (2006)	✓							✓	
Göthe-Lundgren et al. (2002)	✓							✓	
Pudasaini (2021)	✓							✓	
Xie et al. (2023)	✓							✓	
Li et al. (2004)			✓						✓
MirHassani (2008)			✓						✓
MirHassani and Noori (2011)			✓						✓
Yang et al. (2010)			✓						✓

CHAPTER 3

PCSC DESCRIPTION

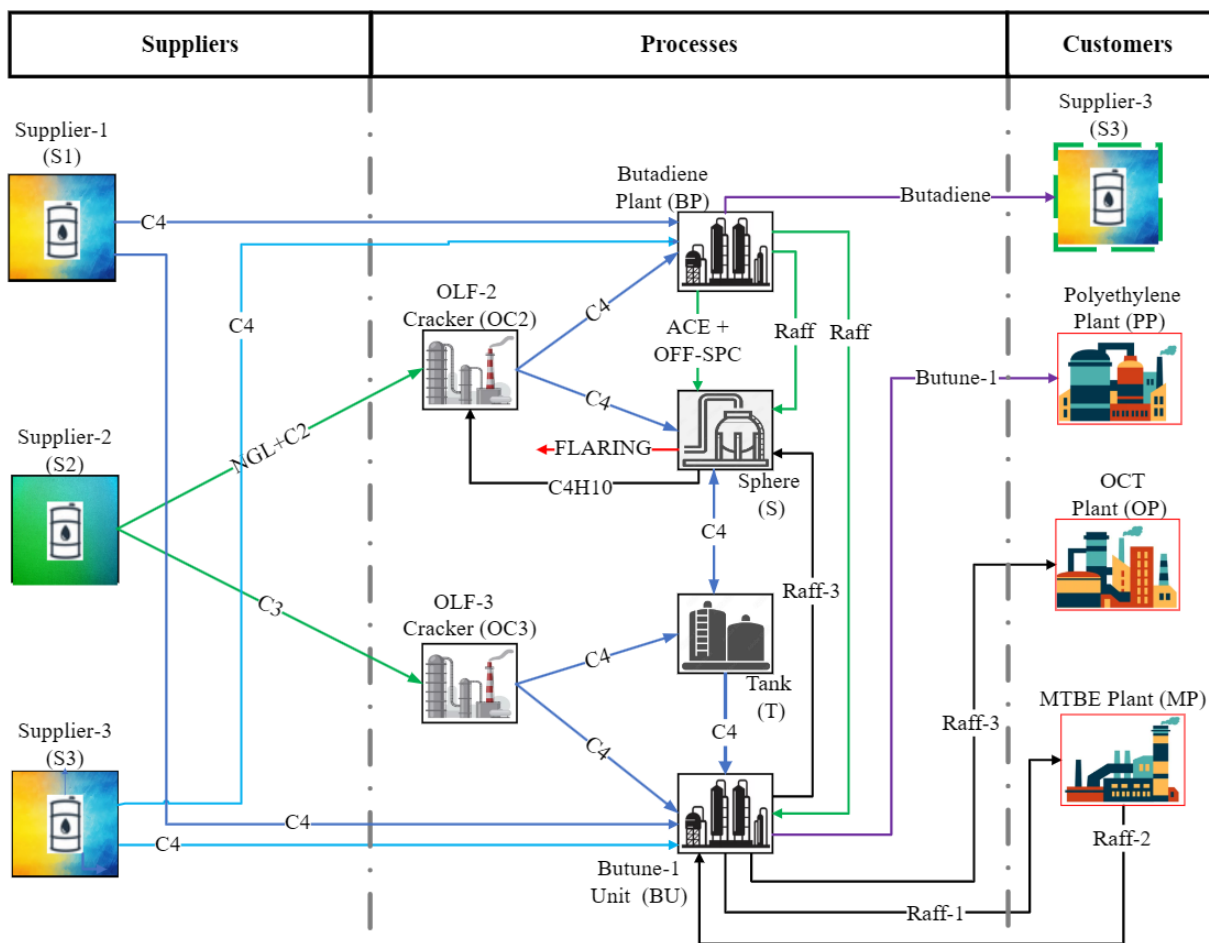
3.1 Network Description

Figure 2 schematics the considered real C₄ SC network in this research. C₄ chemicals in the petrochemical industry include butanes, butylenes, Butadiene, butanols, and methyl Tert Butyl Ethers (MTBE). Production of C₄ involves several activities, from raw materials to the final product, butane-1, distributed over three echelons: raw material supply, processing and storage facilities, and end customers.

C₄, natural gas liquid (NGL C₅+), ethane (C₂), and propane (C₃) are raw materials, starting at echelon 1. Processes, transformations, and storage in the SC's second echelon are among its complicated. The SC includes the OLF, Butadiene, and butene-1 plants, while the C₄ tank and Sphere serve as storage facilities. The OLF plant breaks saturated hydrocarbons into C_nH_{2n} hydrocarbons (Davarnejad et al., 2021). Three plants, OCT, MTBE, and polyethylene, are Butane-1's final customers in the third echelon. Reverse logistics complicates the SCM by requiring different product flows and regulatory compliance.

The raw materials from suppliers are the main feedstocks for Olefin plant crackers. These crackers produce C₄, which includes butane-1, butane-2, butadiene 1-3, and isobutane. These crackers aim to heat saturated hydrocarbons to 850°C to break molecular bonds and

shrink molecules. Ethan (C_2) and NGL (C_5+) go to OLF-2, whereas propane (C_3) goes to OLF-3. The Sphere receives C_4 from OLF-2, whereas the Tank receives C_4 from OLF-3.



[Figure 2 Schematic representation of C_4 supply chain]

The butadiene and butane-1 plants receive the C_4 chemicals produced by crackers. They resort to external supplies when OLF-2 and OLF-3 fail to generate sufficient C_4 for the butadiene and butene-1 plants. The butene-1 unit produces RAF-1, which goes to the MTBE plant for customer 2, and RAF-3, which goes to the OCT plant for customer 1. RAF-3 also goes to the Sphere. The MTBE plant, serving customer 2, returns RAF-2 to

butene-1. In chemical separation terminology, RAFF, short for raffinate, refers to a product with one or more components removed, and extracted materials are known as the extract. The butadiene facility produces Butadiene for supplier 1 and RAFF, ACE, and OFF-Spec. These by-products are further processed in the Sphere. After a reaction cycle, the Sphere is vital to recycling these products into OLF-2. However, controlled flaring is required when the C₄ tank and sphere reach capacity. The controlled flare persists until the inventory drops to 10% of C₄, guaranteeing the fulfillment of inventory levels. ACE stands for acetylene, the simplest alkyne and hydrocarbon, with the chemical formula C₂H₂. OFF-Spec is short for off-specification or out of specification, which refers to a product that deviates from standards and fails to fulfill the requirements.

3.2 Problem Statement

In the real world, PCSC plants often face partial or complete unavailability due to routine maintenance or unexpected shutdowns, significantly reducing or halting production. Regular and routine maintenance is critical to prevent unplanned failures, sustain production rates, and extend the lifespan of equipment. To achieve optimal system performance, operational planning models must incorporate realistic maintenance scheduling. The maintenance schedule and length of different petroleum facilities must be meticulously determined prior to model development.

The suggested MILP optimization model tackles these difficulties by integrating operational and maintenance operations across the PCSC system. By coordinating

production, inventory, and environmental decisions with maintenance schedules, the model ensures the efficient use of resources while meeting operational and maintenance constraints. Its primary objective is to maximize profitability by simultaneously optimizing production planning, inventory control, logistics management, and TAM scheduling for several plants, ensuring efficient maintenance scheduling.

In this context, olefin plants play a pivotal role as highly profitable facilities in the petrochemical industry. As highlighted by Zhang et al. (2017), these plants are integral to processing feedstocks into high-demand products like ethylene and propylene, ensuring profitability and sustainability in the petrochemical supply chain. Key sections of olefin plants are shown in Figure 1, including the sections that contain important equipment, such as feed and furnace, quench and fractionation, compressor and condensation, and hydrocarbon separation. These include critical components like heat exchangers, compressors, furnaces, and distillation columns, as illustrated in Figure 3 below.

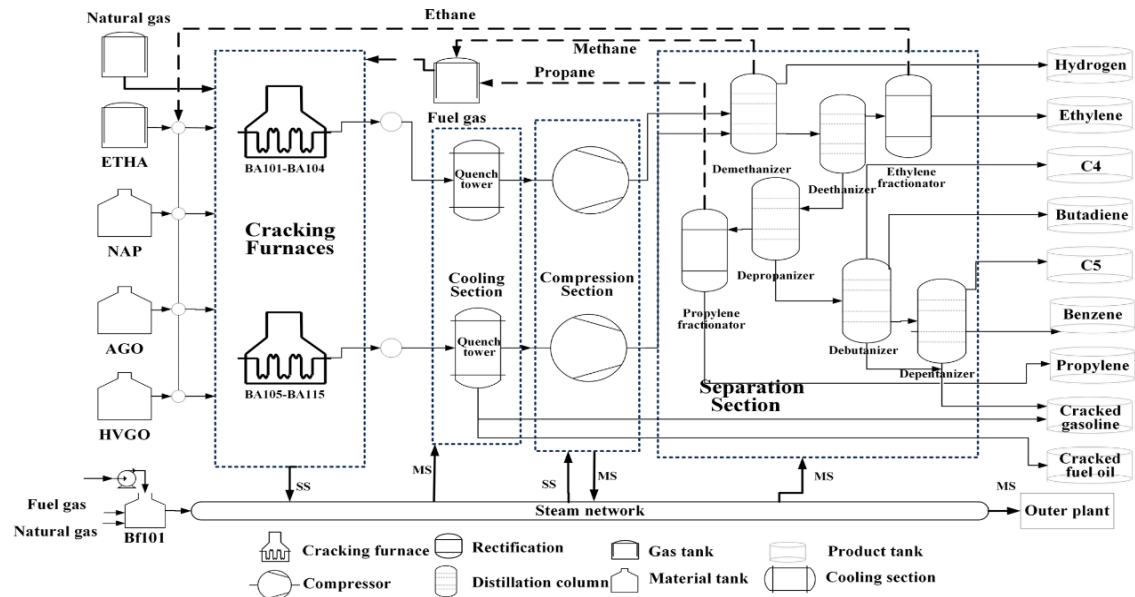


Figure 3 critical equipment in olefin plants Zhang et al. (2017)

Maintenance of these components is vital to sustain smooth operations. For example, heat exchangers undergo regular maintenance 12 times yearly, each lasting 5 days. This maintenance includes cleaning and inspections to prevent fouling and ensure optimal energy efficiency, with an assumed 20% reduction in production capacity during servicing. Compressors are serviced biannually, with each session lasting 14 days, addressing critical tasks such as rotor alignment, seal replacement, and flow stabilization, leading to an assumed 30% reduction in production capacity. Furnaces essential for hydrocarbon cracking are maintained three times annually, with each maintenance period lasting 7 days, focusing on burner inspections, refractory lining repairs, and operational optimization, with an assumed 15% reduction in production capacity. Distillation columns, critical for hydrocarbon separation, are maintained twice a year, with each session lasting 7 days. Maintenance involves structural inspections, cleaning, and material assessments to ensure separation efficiency, with an assumed 35% reduction in production capacity during servicing. These reduction factors are used as assumptions to model and analyze the maintenance scheduling process. These maintenance tasks are dynamically scheduled to avoid overlaps and are staggered across multiple facilities, such as OLF2 and OLF3, ensuring uninterrupted production and minimizing operational disruptions.

The proposed model optimizes maintenance scheduling by dynamically staggering tasks across multiple plants to minimize downtime and ensure operational continuity. That critical equipment undergoes periodic maintenance, with tasks carefully scheduled to avoid overlapping. This approach ensures that maintenance activities are completed efficiently

while maintaining consistent production flows. By strategically prioritizing resource allocation and sequencing tasks, the model reduces downtime, optimizes resource utilization, and enhances operational efficiency. Additionally, inventory management plays a crucial role, ensuring sufficient buffer stock to support operations during planned maintenance or unexpected shutdowns.

Overall, the proposed model effectively integrates operational planning and maintenance scheduling, providing a robust framework to optimize the performance of HCSC plants. This comprehensive approach ensures consistent supply chain operations, maximizes resource utilization, minimizes long-term costs, and promotes the sustainability and efficiency of petrochemical supply chains.

CHAPTER 4

MODEL DEVELOPMENT

The following sections of this chapter explain how the model is developed using an illustrative real-world example. This includes the notations used, the objective the model tries to optimize, and the considered constraints, explicitly focusing on reverse logistics management and environmental limitations.

Mixed-Integer Linear Programming (MILP) is a mathematical optimization technique that seeks to optimize a linear objective function subject to linear equality and inequality constraints. MILP extends traditional linear programming (LP) by incorporating integer decision variables, enabling it to address complex scenarios such as scheduling, resource allocation, and maintenance planning. This method is pivotal for optimizing multi-objective systems, including cost minimization, production stability, and maintenance scheduling, while ensuring compliance with operational constraints.

4.1 Model Assumptions

- **Steady-State Operations:** All production units operate continuously without interruptions or shutdowns.
- **Deterministic Nature:** The optimization problem is deterministic, meaning all inputs, such as supply, demand, costs, and operational parameters, are known with certainty at the time of planning. This ensures precise modeling without incorporating randomness or probabilistic elements.

- **Linear Structure:** The problem is formulated as a Mixed-Integer Linear Programming (MILP) model, where the objective function and constraints are linear, ensuring computational efficiency and compatibility with established optimization techniques.
- **Static Configuration:** The system configuration, including plant structure, equipment capacities, and network design, remains unchanged throughout the planning horizon.
- **Dynamic Demand:** While the problem is deterministic, it accounts for dynamic variations in product demand over the planning horizon, reflecting real-world market behavior.
- **Operational Constraints:** The model incorporates various operational constraints, such as plant capacity, inventory limits, flaring controls, and material balance, ensuring realistic system behavior.
- **Integrated Optimization:** The problem integrates multiple objectives, including production planning, inventory control, and maintenance scheduling, within a single framework to maximize profitability and operational efficiency.
- **Sustainability Considerations:** Environmental constraints, such as minimizing flaring, are embedded in the model to align with sustainability goals.

4.2 Model Notations

Table 3 lists model notations used for developing the optimization model. These include sets, indices, decision variables, and parameters.

Table 3 Model notations

1. Sets/Indices:

i, j : all nodes, where i and $j \in \{S1, S2, S3, OC2, OC3, BP, Sph, Tank, BU, PP, OP, MP\}$

p : set of all products indexed with p , where $p \in \{C2, C3, C4, NGL, C4H10, ACE, OFF-SPC, RAFF, Raff-1, Raff-2, Raff-3, Butadine, Buttune-1\}$
 t : set of time periods indexed with $t \in \{1, 2, 3, \dots, T\}$
 S : set of sections of plant i indexed with s , where $s \in \{\text{heat exchangers, compressor, furnace, distillation column}\}$

2. Decision Variables:

X_{ijpt} : amount of product p transferred from node i to node j at time t
 Inv_{jpt} : amount of inventory for material p storde in node j at time t
 F_t : amount of flaring at time t
 z_t : binary flaring activation variable; 1 if flaring occurs, 0 otherwise.
 R_t : amount of recycling at the time t
 BM_{sit} : 1 if maintenance is active in section s for plant i at time t , 0 otherwise

3. Parameters:

$A_{i,p,t}$: available feedstock supply of product p from supplier i at time t .
 C_j : maximum processing capacity of node j
 CP_{ij} : capacity of the pipeline connecting i to node j
 $IC_{max,j}$: maximum inventory storage capacity at node j
 $IC_{min,j}$: minimum inventory threshold at node j
 D_{pjt} : demand for product p at node j at time t
 $R_{max,j}$: maximum recycling capacity at node j
 $R_{min,j}$: minimum recycling threshold at node j
 TH_f : flaring threshold inventory level (tons)
 Q_f : planned flaring quantity (tons)
 M : sufficient large positive number used to activate or deactivate constraints
 sp_{pt} : selling price per unit of product p at time t
 mc_{pt} : cost of raw material per unit transported in stream X_{ijpt}
 pc_{jpt} : processing and transformation cost at node j of product p at time t
 tc_{ijpt} : transportation cost from node i to node j of product p at time t
 fc_{jt} : flaring cost at node j at time t

ic_{jt} Inventory holding cost at node j at time t
 y_{ijp} : yield of product p on the stream ij , representing the fraction of product p (%).

4.3 Model Constraints

A set of linear constraints has been formulated to identify the feasible area of the model. They are categorized into seven blocks: maintenance planning, supplier feedstock, plant capacity restrictions, inventory capacity, pipe and production, non-negativity constraints, and material balance of the second echelon.

4.3.1 Maintenance Scheduling Constraints

1- Constraint for Maintenance Frequency

The following constraint shown in *Eq. (1)* ensures that each section s of plant i is maintained at least once during the planning horizon.:

$$\sum_{s \in S, t \in T} BM_{sit} \geq 1 \Rightarrow \forall i \quad (2)$$

This ensures that every plant i undergoes at least one maintenance activity during the specified time frame, adhering to the required maintenance schedules.

2- Scenario-1 No Overlapping of Maintenance Within Each Single Plant

The following constraint shown in *Eq. (3)* ensures that no more than one section s of a specific plant i is under maintenance at any given time t :

$$\sum_{s \in S} BM_{sit} \leq 1 \Rightarrow \forall i, t \quad (4)$$

This condition guarantees that maintenance tasks within a single plant are scheduled sequentially, preventing overlap. While one section undergoes maintenance, the other sections remain fully operational, minimizing downtime and maintaining the plant's overall productivity.

3- Scenario-2 No Overlapping of Maintenance Across All Plants

The following constraint shown in *Eq. (5)* ensures that maintenance activities do not overlap across multiple plants at any given time t :

$$\sum_{i \in I, s \in S} BM_{sit} \leq 1 \Rightarrow \forall t \quad (6)$$

This constraint limits maintenance to one section across all plants at any specific time, ensuring that others remain fully operational while one plant undergoes servicing. By enforcing this restriction, the model minimizes disruptions to the hydrocarbon supply chain and maintains consistent production flow.

4- Periodic Maintenance Scheduling:

The periodic maintenance scheduling ensures that maintenance for section s of plant i occurs at regular intervals for each section f_s , which denotes the duration of time between consecutive maintenance activities for plant i . This is carried out by equating the relevant binary variables, ensuring consistent timing between maintenance activities. The relationship is expressed as shown in *Eq. (7)*:

$$BM_{sit} = BM_{si(t+f_s)} \Rightarrow \forall i, s, t \quad (8)$$

If maintenance is performed at time t , the next maintenance activity will occur at time $t+f_s$. This constraint ensures that maintenance tasks follow the predefined periodic schedule.

5- Duration Constraint:

This constraint, expressed as shown in *Eq. (9)*, ensures that during the maintenance window of exactly d_s days starting from a specific time t , no additional maintenance starts occur for the same unit. The binary variable BM_{sit} determines whether maintenance starts for section s of plant i on day t , and k represents the time index covering the days within the maintenance duration. By restricting maintenance initiations during the active maintenance window of d_s consecutive days, this constraint prevents overlapping maintenance activities across the planning horizon.

$$\sum_{k=t}^{t+d_s-1} BM_{sik} \leq 1 \Rightarrow \forall t \in \{1, \dots, T - d_s + 1\} \quad (10)$$

4.3.2 Production Planning and Inventory Control Constraints

(1) Material balance constraints: *Eqs (11) - (12)* ensures the conservation of mass across the network by enforcing that the total incoming and outgoing flows at each node remain balanced. At node OC3, material balance is maintained for C4 components, ensuring that the amount received from S2 is either transferred to the Butadiene Unit (BU) or stored in a tank, *Eq. (13)*. This prevents any loss of material during the transfer. At node OC2, the balance is maintained for C4 components, ensuring that the total flow from sources like S2 and Sphere equals the outgoing flow to destinations such as BP and Sphere, *Eq. (14)*. Additionally, for ACE and OFF-SPC, the inflow to BP from OC2, S1, and S3 must match

the amount sent to Sphere, Eq. (15). The balance for Raffinate at BP ensures that all material received from OC2, S1, and S3 is distributed between Sphere and BU, Eq. (16), while the Butadiene balance guarantees that all material at BP is sent to S3, Eq. (17).

For node BU, the balance constraints regulate the movement of different Raffinate and Buttune materials. Raffinate-1 material received from BP, OC3, storage tanks, and other intermediate units must be passed forward to MP, maintaining the flow of processed material, Eq. (18). Similarly, for Raffinate-3, the total inflow from BP, OC3, and storage tanks must match the outflow directed to Sphere and OP, Eq. (19). Lastly, the Buttune-1 balance ensures that all incoming material from BP and other sources is properly distributed to Sphere and OP, ensuring efficient utilization within the system, Eq. (20). These constraints collectively uphold the integrity of material flow, ensuring that no excess or shortage occurs across the network.

$$y_{S2,OC3,C4}X_{S2,OC3,C3,t} = X_{OC3,BU,C4,t} + X_{OC3,Tank,C4,t} \Rightarrow \forall t \quad (13)$$

$$\sum_{p \in \{C2, NGL\}} y_{S2,OC2,C4}X_{S2,OC2,p,t} + y_{Sphere,OC2,C4}X_{Sphere,OC2,C4H10,t} \\ = \sum_{j \in \{BP, Sphere\}} X_{OC2,j,C4,t} \Rightarrow \forall t \quad (14)$$

$$y_{OC2,BP,p}X_{OC2,BP,C4,t} + \sum_{i \in \{S1, S3\}} y_{i,BP,p}X_{i,BP,C4,t} = X_{BP,sphere,p,t} \\ \Rightarrow p \in \{ACE, OFF - SPC\}, \forall t \quad (15)$$

$$y_{OC2,BP,RAFF}X_{OC2,BP,C4,t} + \sum_{i \in \{S1, S3\}} y_{i,BP,RAFF}X_{i,BP,C4,t} = \\ \sum_{j \in \{Sphere, BU\}} X_{BP,j,RAFF,t} \Rightarrow \forall t \quad (16)$$

$$\begin{aligned}
y_{OC2,BP,Butadine}X_{OC2,BP,C4,t} + \sum_{i \in \{S1,S3\}} y_{i,BP,Butadine}X_{i,BP,C4,t} \\
= X_{BP,S3,Butadine,t} \Rightarrow \forall t
\end{aligned} \tag{17}$$

$$\begin{aligned}
y_{BP,BU,Raff-1}X_{BP,BU,Raff,t} + \sum_{i \in OC3,Tank,MP,S1,S3} y_{i,BU,Raff-1}X_{i,BU,C4,t} = \\
X_{BU,MP,Raff-1,t} \Rightarrow \forall t
\end{aligned} \tag{18}$$

$$\begin{aligned}
y_{BP,BU,Raff-3}X_{BP,BU,Raff,t} + \sum_{i \in OC3,Tank,MP,S1,S3} y_{i,BU,Raff-3}X_{i,BU,C4,t} = \\
\sum_{j \in \{Sphere,OP\}} X_{BU,j,Raff-3,t} \Rightarrow \forall t
\end{aligned} \tag{19}$$

$$\begin{aligned}
y_{BP,BU,Buttune-1}X_{BP,BU,Raff,t} + \sum_{i \in OC3,Tank,MP,S1,S3} y_{i,BU,Buttune-1}X_{i,BU,C4,t} = \\
\sum_{j \in \{Sphere,OP\}} X_{BU,j,Buttune-1,t} \Rightarrow \forall t
\end{aligned} \tag{20}$$

(3) *Supplier feedstock*: The feedstock supply from the three suppliers in the C4 supply chain is regulated by Eqs. (21) and (22). Supplier 2 (S2) serves as the primary supplier, delivering a fixed quantity of C2, C3, and NGL. When shortages arise at the Butadiene plant (BP) and Butene-1 unit (BU), supplementary supply is sourced from Supplier 1 (S1) and/or Supplier 3 (S3).

$$\sum_{j \in \{OC2,OC3\}} X_{i,j,p,t} \leq A_{i,p,t} \Rightarrow i \in \{S2\}, p \in \{C2,C3,NGL\}, \forall t \tag{21}$$

$$\sum_{j \in \{BP,BU\}} X_{i,j,p,t} \leq A_{i,p,t} \Rightarrow i \in \{S1,S3\}, p \in \{C4\}, \forall t \tag{22}$$

(4) *Plant capacity constraints*: Eqs. (23)-(26) limits the total amount of product, p , entering each processing plant, ensuring it does not exceed the plant's Capacity, C_{jpt} adjusted for maintenance impacts. At OC2, the sum of incoming C2, NGL, and C4H10, considering capacity reduction due to maintenance activities, must remain within the

plant's processing limit, Eq. (23). Similarly, the inflow of C3 into OC3 is constrained by its maximum Capacity, adjusted for maintenance, as shown in Eq. (24). For BP, the total C4 flow from sources such as S1, S3, and OC2 must not surpass its processing capability, accounting for any reductions caused by ongoing maintenance, Eq. (25). Finally, at BU, the combined inflows of Raffinate from BP and MP, as well as C4 from sources like S1, S3, OC3, and storage tanks, must remain within the plant's Capacity, reflecting maintenance-related adjustments, Eq. (26). These constraints ensure that no processing facility is overloaded, maintaining an efficient operation. *Pipeline and Production Flow Constraints:* Eq. (27) restricts the transportation flow of all products, p , through pipelines between nodes i and j to their respective pipeline capacities, C_{ijpt} .

$$X_{S2,OC2,C2,t} + X_{S2,OC2,NGL,t} + X_{Sphere,OC2,C4H10,t} \leq C_{OC2} \left(1 - \sum_{s \in S} BM_{sit} \cdot RF_s \right) \Rightarrow \forall t \quad (23)$$

$$X_{S2,OC3,C3,t} \leq C_{OC3} \left(1 - \sum_{s \in S} BM_{sit} \cdot RF_s \right) \Rightarrow \forall t \quad (24)$$

$$\sum_{i \in \{S1, S3, OC2\}} X_{i,BP,C4,t} \leq C_{BP} \left(1 - \sum_{s \in S} BM_{sit} \cdot RF_s \right) \Rightarrow \forall t \quad (25)$$

$$\sum_{i \in \{BP, MP\}} X_{i,BU,Raff,t} + \sum_{i \in \{S1, S3, OC3, Tank\}} X_{i,BU,C4,t} \leq C_{BU} \left(1 - \sum_{s \in S} BM_{sit} \cdot RF_s \right) \Rightarrow \forall t \quad (26)$$

$$X_{i,j,p,t} \leq CP_{i,j,p,t} \Rightarrow \forall i, j, p, t \quad (27)$$

(5) Demand Constraints (With Maintenance):

The following constraints, expressed in *Eqs. (28)-(29)*, ensure that the demand for products and byproducts at the terminals is met while accounting for maintenance activities that may reduce available supply. The supply of Butadiene from BP to S3, adjusted for maintenance impacts, must match the demand at S3, as shown in Eq. (30). Similarly, the flow of Butene-1 from BU to PP must satisfy the demand at PP while considering any supply reduction

due to maintenance, as expressed in Eq. (31). In the same manner, the shipments of Raffinate-2 from BU to OP Eq. (32) and Raffinate-1 from BU to MP Eq. (33) are adjusted for maintenance impacts to fulfill their respective demand levels. These constraints ensure system reliability by aligning product delivery with demand requirements, even under partial capacity reductions due to maintenance activities.

$$X_{BP,S3,Butadine,t} \cdot \left(1 - \sum_{s \in S} BM_{sit} \cdot RF_S\right) = D_{Butadine,S3,t} \Rightarrow \forall t \quad (34)$$

$$X_{BU,PP,Buttune-1,t} \cdot \left(1 - \sum_{s \in S} BM_{sit} \cdot RF_S\right) = D_{Buttune-1,PP,t} \Rightarrow \forall t \quad (35)$$

$$X_{BU,OP,Raff-2,t} \cdot \left(1 - \sum_{s \in S} BM_{sit} \cdot RF_S\right) = D_{Raff-2,OP,t} \Rightarrow \forall t \quad (36)$$

$$X_{BU,MP,Raff-1,t} \cdot \left(1 - \sum_{s \in S} BM_{sit} \cdot RF_S\right) = D_{Raff-1,MP,t} \Rightarrow \forall t \quad (37)$$

(6) *Inventory capacity constraints*: Eqs. (38)-(43) regulate storage levels at the Sphere and Tank units to ensure they operate within their designated limits. The Sphere maintains minimum and maximum capacities, preventing overstocking or shortages, Eq. (38). To enhance safety and prevent excessive inventory accumulation, Eq. (39) ensures that flaring is triggered only when the inventory level at time $t-1$ reaches or exceeds the threshold TH_f . The large constant M (a sufficiently large positive number) is used to deactivate this constraint when $z_I=0$, preventing unnecessary flaring. Eq. (40) imposes an upper bound on the flared quantity, restricting it to the planned flaring level Q_f . The term $M(1-z_I)$ ensures that this constraint is inactive when flaring is not triggered ($z_I=0$). Eq. (41) enforces a lower bound on the flared quantity, ensuring that when flaring is activated ($z_I=1$), the flared

amount is exactly Q_f . If flaring is not triggered ($z_f=0$), this constraint is relaxed using the large constant M .

The Tank storage unit has a maximum capacity of 9,600 tons, ensuring that incoming and outgoing flows are balanced accordingly, Eq. (42). To maintain inventory feasibility, both storage units must operate within their specified limits at all times, Eq. (43), preventing operational disruptions due to excessive or insufficient storage. (7) *Recycling Control Constraints*: Eq. (44) manages the Sphere's recycling process, where excess C4 is redirected back to the Olefin Cracker (OC2). The recycling flow must remain within the minimum and maximum limits of 72 and 456 tons, respectively. Finally, (8) *Decision Variables Classification*: Eq. (45) classifies all decision variables as non-negative, ensuring no negative values exist for transported products, inventories, or flaring amounts.

$$I_{sphere,t} = I_{sphere,t-1} + X_{Tank,sphere,C4,t} + X_{BU,sphere,Raff-3,t} + \sum_{p \in \{ACE, OFF-SPC, RAFF\}} X_{BP,sphere,p,t} - (X_{sphere,OC2,C4H10,t} + X_{sphere,Tank,C4,t} + F_t) \Rightarrow \forall t \quad (38)$$

$$I_{sphere,t-1} \geq TH_F - M(1 - z_1) \Rightarrow \forall t > 1 \quad (39)$$

$$F_t \leq Q_F + M(1 - z_1) \Rightarrow \forall t > 1 \quad (40)$$

$$F_t \geq Q_F - M(1 - z_1) \Rightarrow \forall t > 1 \quad (41)$$

$$I_{Tank,t} = I_{Tank,t-1} + X_{sphere,Tank,C4,t} + X_{OC3,Tank,C4,t} - X_{Tank,BU,C4,t} - X_{Tank,sphere,C4,t} \Rightarrow \forall t \quad (42)$$

$$IC_{min,j} \leq I_{jt} \leq IC_{max,j} \Rightarrow j \in \{Sphere, Tank\}, \forall t \quad (43)$$

$$R_{min,Sphere} \leq X_{sphere,OC2,C4H10,t} \leq R_{max,Sphere} \Rightarrow \forall t \quad (44)$$

$$X_{ijpt}, I_{jt}, F_t \geq 0 \Rightarrow \forall i, j, p, t \quad (45)$$

4.4 Model Objective Function

The objective function, Eq. (46) , is designed to maximize total profit over the planning horizon by optimizing production, material flow, inventory management, and operational costs. This function incorporates various economic factors to ensure an optimal balance between revenue and costs while also applying a discount rate (dr) to adjust the total profit to its present value, ensuring an accurate financial assessment over time.

The *first term* represents revenue generation, accounting for the earnings obtained from selling products to final customers at different terminals. This maximizes sales income by strategically allocating product flow based on demand and profitability. The *second term* captures procurement costs, which include the expenses associated with acquiring raw materials from suppliers. This ensures that procurement decisions are made efficiently, minimizing raw material costs without compromising production needs.

The *third term* considers processing costs, which reflect the expenses incurred when transforming raw materials into finished products at different processing units such as BP, OC2, and BU. Optimizing these costs is crucial for maintaining cost-effective operations within the production facilities. The *fourth term* accounts for flow costs, which include transportation expenses for moving products between supply chain nodes. This term ensures that logistical efficiency is maintained while minimizing unnecessary transportation expenditures.

The *fifth term* includes flaring and inventory costs, which impose penalties on excess inventory storage at the Sphere and Tank units and controlled flaring events at the Sphere.

These costs are introduced to prevent excessive accumulation of products and enforce efficient inventory management.

The *final term* includes maintenance costs, which are only incurred when maintenance is scheduled for a section of a plant. These costs reflect the expenses associated with scheduled maintenance activities across the processing units.. If maintenance occurs, these costs are applied; if no maintenance is scheduled, there are no associated costs.

$$\begin{aligned}
 \text{Maximize Profit} = & \sum_t (1 + dr)^{-(t-1)} \\
 & \left[\sum_{\{i,j,p\} \in \{BP,S3 \text{ Butadine}\}\{BU,PP,Butune-1\}\{BU,OP,Raff-3\}\{BU,MP,Raff-1\}\{BU,MP,Raff-2\}} sp_{pt} X_{ijpt} \right. \\
 & - \left(\sum_{\{i,j,p\} \in \{S1,BP,C4\}\{S1,BU,C4\}\{S3,BP,C4\}\{S3,BU,C4\}\{S2,OC2,NGL\}\{S2,OC2,C2\}\{S2,OC3,C3\}} mc_{p,t} X_{ij,p,t} \right. \\
 & + \sum_{\{i,j,p\} \in \{S2,OC2,NGL\}\{S2,OC2,C2\}\{S2,OC3,C3\}\{OC2,BP,C4\}\{OC3,BU,C4\}} pc_{jpt} X_{ijpt} \\
 & + \sum_{ijp \in \{all \text{ Connections}\}} tc_{ijpt} X_{ijpt} + fc_{Sphere,t} F_t + \sum_{j \in \{Sphere,Tank\}} ic_{jt} I_{jt} + Cm \\
 & \left. \cdot \sum_{i \in I, s \in S} BM_{sit} \right) \Bigg]
 \end{aligned} \tag{47}$$

CHAPTER 5

CASE STUDY

This part utilizes a real-life Saudi Arabian C₄ supply chain to implement the proposed optimization methodology, depicted in Figure 1, and analyzes the numerical results. The system comprises 12 nodes, including critical facilities and storage, with demand originating from Supplier 1 for the Butadiene plant. Plants and inventories are represented as nodes to facilitate tracking material transfers. Initial inventory levels for the C₄ sphere and C₄ tank are set at 10% of capacity, serving as safety stock to buffer against uncertainties. The model ensures inventory levels remain within operational limits, preventing flaring and minimizing the risk of shortages.

Maintenance activities are integrated into the model for two critical plants, OLF2 and OLF3, which play a key role in the C₄ supply chain. These plants are divided into sections, each containing critical equipment depicted in Figure 3. For furnaces, compressors, and heat exchangers, it is assumed that each section has two units of each type, allowing for partial maintenance while the other unit remains operational. In contrast, the distillation column is treated as a single unit per section, enabling partial maintenance while maintaining reduced production capacity through predefined reduction factors. Maintenance scheduling is dynamically optimized to ensure minimal disruption to operations, balancing reduced capacity with inventory utilization to meet demand effectively.

By incorporating maintenance impacts, the model accounts for operational constraints while managing inventory and supply adjustments. It ensures that the supply chain continues to operate efficiently during maintenance periods, preserving equipment reliability and meeting demand requirements. This integration highlights the importance of aligning maintenance scheduling with production planning to optimize overall performance in the C₄ supply chain.

5.1 Collected Data

The model is done under this configurations:

1. Pipe and Production Capacity	
Maximum amount of C ₄ from Supplier1 to Butadiene Plant	144
Maximum amount C ₄ from Supplier1 to Butene-1 Unit	144
Maximum amount of C ₄ from Supplier3 to Butadiene Plant	816
Maximum amount of C ₄ from OLF-2 Plant to Sphere	816
The max amount of Raff is 42% from Butadiene Feedstock to Sphere or Butene-1 unit	210
The max amount of Acetylene is 5% from Butadiene Feedstock to Sphere	25
The max amount of Off-spec is 3% from Butadiene Feedstock to Sphere	15
Maximum amount C ₄ from tank to Butene-1 unit	480
Maximum amount C ₄ from OLF-3 Plant to C ₄ Tank	480
Maximum amount of C ₄ from OLF-3 Plant to Butene-1 unit	480

Maximum mount of Raff-2 from MTBE to Butene-1	480
2. Feedstock Capacity Constraints:	
Max amount of C ₃ from Supplier2 to OLF-3 Plant	482.1
Max amount of NGL from Supplier2 to OLF-2	605.02
Max amount of C ₂ from Supplier2 to OLF-2	206.88
3. Inventory Capacity Constrains	
Maximum capacity of C ₄ sphere	3240
The minimum amount of C ₄ that the C ₄ sphere holds to be safe in emergency cases	324
Maximum capacity of C ₄ Tank	9860
The minimum amount of C ₄ that the C ₄ Tank holds to be safe in emergency cases	986
4. Production Constraints:	
The max amount of C ₄ Produced is 50% from Butadiene Plant to Supplier1	408
	320
The max amount of Raff-3 is 40% from Butene Feedstock to OLF-2 Plant or OCT	480
The max amount of Raff-1 is 60% from Butene-1 to MTBE	
5. Butadiene plant:	
$X_{BP,S3,BU,t} = 0.5 * (X_{S3,BU,C4,t} + X_{S1,BP,C4,t} + X_{OC2,BU,C4,t})$	
The above material balance equation ensures that the flow of C ₄ material from BP to S ₃ , destined for BU, is proportional to 50% of the Total inflow from three sources: S ₃ , S ₁ , and OC ₂ .	
$X_{BP,S,ACE,t} = 0.05 * (X_{S3,BU,C4,t} + X_{S1,BP,C4,t} + X_{OC2,BU,C4,t})$	
The above material balance equation ensures that the flow of C ₄ material from BP to Shpere, destined for ACE, is proportional to 5% of the Total inflow from three sources: S ₃ , S ₁ , and OC ₂ .	

$$X_{BP,S,off,t} = 0.03 * (X_{S3,BU,C4,t} + X_{S1,BP,C4,t} + X_{OC2,BU,C4,t})$$

The above material balance equation ensures that the flow of C4 material from BP to BU and Sphere, destined for off-spec, is proportional to 3% of the Total inflow from three sources: S3, S1, and OC2.

$$X_{BP,BU,RAFF,t} + X_{BP,S,RAFF,t} = 0.42 * (X_{S3,BU,C4,t} + X_{S1,BP,C4,t} + X_{OC2,BU,C4,t})$$

The above material balance equation ensures that the flow of C4 material from BP to BU and Sphere, destined for RAFF, is proportional to 42% of the Total inflow from three sources: S3, S1, and OC2.

If Statements

$$X_{S1,BP,C4,t} \leq \text{If } (X_{S3,BU,C4,t} = 144 \text{ Then } 240, 0 \text{ otherwise})$$

If the flow of C4 material from Supplier 3 (S3) to the Butene-1 Unit (BU) is 144 at time t, then the maximum flow of C4 material from Supplier 1 (S1) to the Butadiene Plant (BP) is 240.

Otherwise, no flow (0) is allowed from S1 to BP.

6. Sphere

$$X_{OC2,S,C4,t} + X_{BP,S,ACE,t} + X_{BP,S,RAF,t} + X_{BP,S,OFF,t} + X_{BU,S,OC3,t} + X_{T,S,RAF3,t} = X_{S,OC2,C4H8,t} + X_{S,T,C4,t} + \text{FLARE}$$

The equation balances the total inflow to the Sphere from various sources, including OC2, BP, BU, and Tank, with the total outflow to OC2, Tank, and flaring.

If Statements

$$I_{S,C4,t} = \text{if } (I_{S,C4,t-1} + X_{OC2,S,C4,t} + X_{BP,S,RAFF,t} + X_{BP,S,ACE,t} + X_{BP,S,off,t} + X_{T,S,C4,t} + X_{BU,S,R3,t} - X_{S,OC2,C4H8,t} \geq 2916, \text{ then } 2268, \text{ otherwise } I_{S,C4,t-1} + X_{OC2,S,C4,t} + X_{BP,S,RAFF,t} + X_{BP,S,ACE,t} + X_{BP,S,off,t} + X_{BU,S,R3,t} + X_{T,S,C4,t} - X_{S,OC2,C4H8,t});$$

If the total inflow to the Sphere, accounting for material flows and prior inventory, exceeds or equals 2916 at time t, the inventory level is set to 2268.

Otherwise, the inventory level is updated based on the total inflows and outflows.

7. Olf-3 cracker:

$$X_{S2,OC3,C3,t} = X_{OC3,T,S1,t} + X_{OC3,BU,C4,t}$$

The equation ensures that the total flow of C3 material from Supplier

If Statements

$X_{OC3,T,C4,t} = \text{If } (X_{OC3,BU,C4,t} = X_{S2,OC3,C3,t} \text{ OR BU is Full Then } X_{S2,OC3,C3,t} - X_{OC3,BU,C4,t},$
 $0 \text{ otherwise})$

If the flow of C4 material from OC3 to BU equals the flow from S2 to OC3 or if BU (Butene-1 Unit) is at full capacity, the remaining material is redirected from OC3 to the Tank. Otherwise, no flow occurs from OC3 to the Tank.

8. Butene -1 plant:

$$X_{S3,BU,C4,t} + X_{S1,BU,C4,t} + X_{OC3,BU,C4,t} + X_{T,BU,C4,t} + X_{BP,BU,RAF,t} + X_{MP,BU,RAF2,t} = X_{BU,PP,BUT1,t} \\ + X_{BU,OP,RAF3,t} + X_{BU,MP,RAF1,t} + X_{BU,S,RAF3,t}$$

The equation above ensures that the total inflow of C4 and RAFF materials to the Butene-1 Unit (BU) from multiple sources: Supplier 3 (S3), Supplier 1 (S1), OC3, Tank, BP, and MP, matches the total outflow from BU to various destinations. These include the Polypropylene Plant (PP), OCT Plant (OP), MP, and the Sphere (S), ensuring material balance across the system.

$$X_{BU,MP,RAF3,t} = 0.6 * (X_{S3,BU,C4,t} + X_{S1,BU,C4,t} + X_{T,BU,C4,t} + X_{BP,BU,S,t} + X_{OC3,BU,C4,t})$$

The above equation ensures that the flow of RAFF3 material from the Butene-1 Unit (BU) to the MP is proportional to 60% of the total inflow of C4 material to BU.

$$X_{BU,OP,R3,t} + X_{BU,S,R3,t} = 0.4 * (X_{S3,BU,C4,t} + X_{S1,BU,C4,t} + X_{T,BU,C4,t} + X_{BP,BU,RAF,t} + X_{OC3,BU,C4,t})$$

The equation ensures that the combined flow of RAFF3 material from the Butene-1 Unit (BU) to the OP and Sphere is proportional to 40% of the total inflow of C4 material to BU.

$$X_{MP,BU,R2,t} = 0.68 * X_{BU,MP,RAF1,t}$$

The equation ensures that 68% of the RAFF1 material flow from the Butene-1 Unit (BU) to the MP is converted into RAFF2 material for further processing within the MP.

$$X_{BP,BU,RAFF,t} = 0.4 * (F_{S,t} - X_{S3,BU,C4,t} - X_{S1,BU,C4,t})$$

The equation ensures that the flow of RAFF material from the Butadiene Plant (BP) to the Butene-1 Unit (BU) is 40% of the remaining feedstock (FS) after subtracting the contributions from Supplier 3 (S3) and Supplier 1 (S1) to BU.

$$X_{OC3,BU,C4,t} + X_{T,BU,C4,t} = 0.6 * (F_{S,t} - X_{S3,BU,C4,t} - X_{S1,BU,C4,t})$$

The equation ensures that the combined flow of C4 material from OC3 and Tank to the Butene-1 Unit (BU) equals 60% of the remaining feedstock (FS) after subtracting the contributions from Supplier 3 (S3) and Supplier 1 (S1) to BU.

If Statements

$$X_{S1,BU,C4,t} \leq \text{If } (X_{S3,BU,C4,t} = 144 \text{ Then } 240, 0 \text{ otherwise})$$

If the flow of C4 material from Supplier 3 (S3) to BU equals 144, the flow from Supplier 1 (S1) to BU is capped at 240.

Otherwise, no flow is allowed from S1 to BU.

$$X_{T,BU,C4,t} \leq \text{If } (X_{OC3,BU,C4,t} = 480 \text{ Then } 480, 0 \text{ otherwise})$$

If the flow of C4 material from OC3 to BU equals 480, the flow from Tank (T) to BU is also capped at 480. Otherwise, no flow is allowed from Tank to BU.

$$X_{BU,S,R3,t} = \text{If } (X_{S2,OC3,C3,t} \leq 414 \text{ Then } 0.4 * (X_{S3,BU,C4,t} + X_{S1,BU,C4,t} + X_{T,BU,C4,t} + X_{BP,BU,RAFF,t} + X_{OC3,BU,C4,t}), 0 \text{ otherwise})$$

If the flow of C3 material from OC3 to BU is less than or equal to 414, the flow of RAFF3 from BU to Sphere (S) is set to 40% of the combined inflow from S3, S1, T, BP, and OC3 to BU. Otherwise, no flow of RAFF3 from BU to S is allowed.

9. Tank:

$$I_{T,C4,t} \geq X_{T,BU,RAFF,t} + X_{T,S,C4,t}$$

The inventory of C4 in the Tank (T) at time t must be greater than or equal to the total outflows of RAFF material to the Butene-1 Unit (BU) and C4 material to the Sphere (S).

$$I_{T,C4,t} = I_{T,C4,t-1} + X_{OC3,T,C4,t} - X_{T,BU,C4,t} - X_{T,S,C4,t}$$

The inventory of C4 in the Tank (T) at time t is determined by the previous inventory, plus the inflow from OC3, minus the outflows to the Butene-1 Unit and the Sphere

If Statements

$$X_{T,S,C4,t} \leq \text{If } (I_{T,C4,t-1} \geq 1500 \text{ Then } 480, 0 \text{ otherwise})$$

If the inventory of C4 in the Tank at the previous time step is greater than or equal to 1500, the flow of C4 from the Tank (T) to the Sphere is capped at 480. Otherwise, no flow is allowed from the Tank to the Sphere.

10. Recycling:

$$X_{S,OC2,C4H8,t} \text{ is between } 72 \text{ and } 456$$

The flow of recycled C4H8 from the Sphere (S) back to OC2 is constrained to be between a minimum of 72 and a maximum of 456 units.

If Statements

$$X_{S,OC2,C4H8,t} \geq \text{if } (X_{S2,OC2,C2,t} \leq 816, \text{ then } 456, \text{ otherwise } 72)$$

If the flow of C2 material from Supplier 2 (S2) to OC2 is less than or equal to 816, the recycling flow is capped at 456. Otherwise, the minimum recycling flow is set at 72.

11. Environmental (flaring):

$$F_t = \text{if } (I_{S,C4,t-1} \geq 2915, \text{ then } I_{S,C4,t-1} + X_{OC2,S,C4,t} + X_{BP,S,RAFF,t} + X_{BP,S,ACE,t} + X_{BP,S,off,t} + X_{BU,S,R3,t} + X_{T,S,C4,t} - X_{S,OC2,C4H8,t} - 2916 + 648, \text{ otherwise } 0)$$

If the C4 inventory in the Sphere exceeds or equals 2915, flaring is activated to maintain operational safety. The flared amount equals the excess inventory after accounting for inflows from OC2, BP, BU, and Tank, minus outflows to OC2 and recycling, adjusted for a buffer of 648. Otherwise, no flaring occurs.

- **Heat Exchangers:**

- Maintenance involves cleaning, inspecting, and repairing components to prevent fouling and ensure efficient heat transfer.
- **Duration:** Each occurrence lasts for 5 days.
- **Frequency:** This happens every 60 days in a year.
- **Reduction Factor:** 20% reduction in production capacity during maintenance.
- **Maintenance Cost:** \$400 per day.

- **Compressors:**

- Maintenance tasks include lubrication, rotor alignment, and seal replacements, ensuring pressure stability and flow consistency.
- **Duration:** Each occurrence lasts for 10 days.
- **Frequency:** This happens every 180 days in a year.
- **Reduction Factor:** 30% reduction in production capacity during maintenance.
- **Maintenance Cost:** \$600 per day.

- **Distillation Columns:**
 - Tasks include cleaning trays, inspecting packing materials, and ensuring structural integrity to maintain separation efficiency.
 - **Duration:** Each occurrence lasts for 7 days.
 - **Frequency:** This happens every 180 days in a year.
 - **Reduction Factor:** 35% reduction in production capacity during maintenance.
 - **Maintenance Cost:** \$350 per day.
- **Furnaces:**
 - Maintenance involves inspecting burners, repairing refractory linings, and ensuring energy efficiency.
 - **Duration:** Each occurrence lasts for 7 days.
 - **Frequency:** This happens every 120 days in a year.
 - **Reduction Factor:** 15% reduction in production capacity during maintenance.
 - **Maintenance Cost:** \$500 per day.

CHAPTER 6

RESULTS AND SENSITIVITY ANALYSIS

6.1 Optimization of the PCSC

In order to evaluate the material balance of the input and output flow of the products, the total average input products in the Butene-1 Unit and Butadiene Plant are presented in Table 4. The output flow of products from the Butene-1 Unit and Butadiene Plant is obtained in Tables 5 and 6.

Table 4 Total average input in the system

Amount of C ₄ in:	Total average (Ton/day)
Butene-1 Unit	945.45
Butadiene Plant	855.3

Table 5 Average product output from the Butadiene Plant

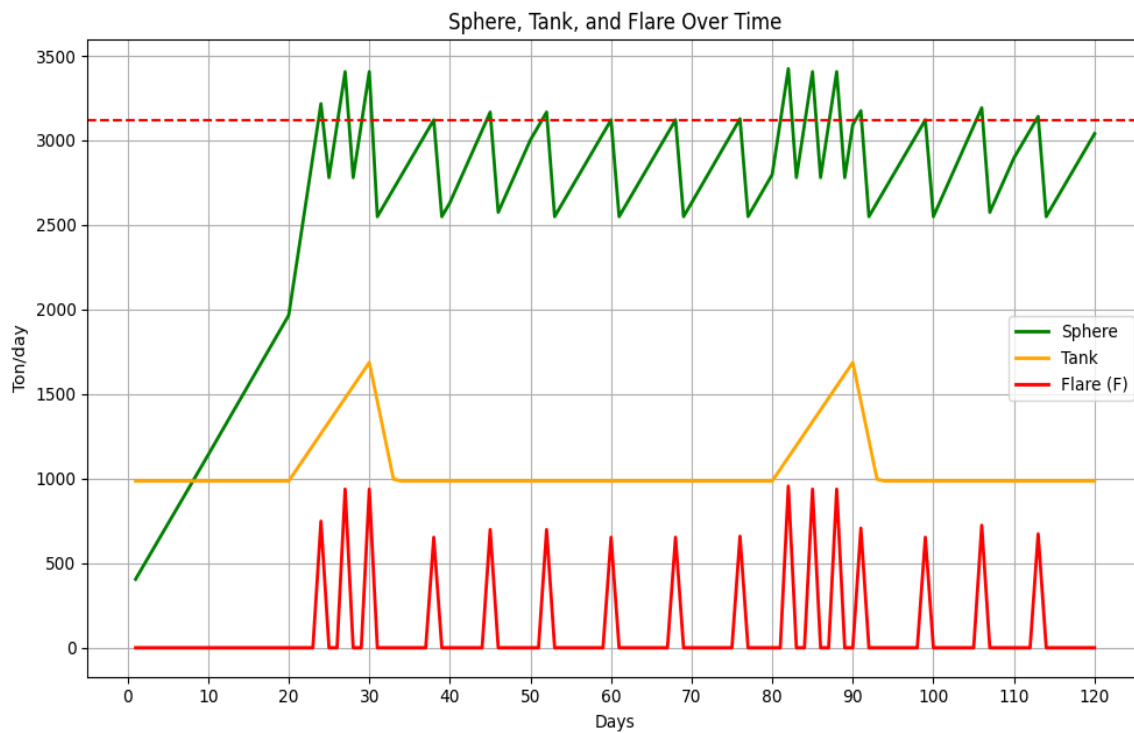
Products	Flow (Ton/day)
Butadiene	427.65
Raffinate	359.226
Acetylenes	42.765
Off-Spec	25.659

Table 6 Average product output from the Butene-1 Unit

Products	Flow (Ton/day)
Butene-1	472.725
Raffinate-3	283.635
Raffinate-1	189.09

After computing the outputs in this system, it was ensured that the material balance was obtained in order to have a consistent outcome. In accordance with the material balance constraints, the objective of profit maximization is to maintain a low flaring cost. The Green environmental impact analysis shows that the flaring amounts to 133.73 tons daily, whereas the daily profit is \$1.25M.

Figure 4 illustrates the dynamic behavior over 120 days of the C₄ PCSC as modeled in the study. The sphere inventory shows an initial increase due to the accumulation of feedstock and recycled materials, with a clear threshold set at 2916 tons, as shown in the figure below the maximum sphere inventory capacity of 3240 tons.



[Figure 4 Optimal sphere, tank inventory level and flaring]

The periodic peaks and drops in the sphere inventory highlight the interplay between production, recycling, and flaring, designed to optimize resource utilization while minimizing emissions. Once the threshold is reached, controlled flaring is triggered to prevent overcapacity, ensuring inventory levels remain within operational constraints.

Meanwhile, the tank inventory remains stable during normal operations, with fluctuations observed during periods of increased demand or production adjustments to maintain a balance between supply and demand. The periodic spikes in flaring align with the model's constraints, demonstrating the system's ability to handle excess production in a controlled and sustainable manner. These outcomes are consistent with the study's proposed optimization framework, which integrates production planning, inventory management, and reverse logistics.

The C₄ supply chain system effectively demonstrates the model's capacity to minimize environmental impacts through controlled flaring while maintaining inventory stability and ensuring efficient resource utilization across the supply chain. This behavior validates the model's ability to achieve a balance between operational efficiency, sustainability, and profitability.

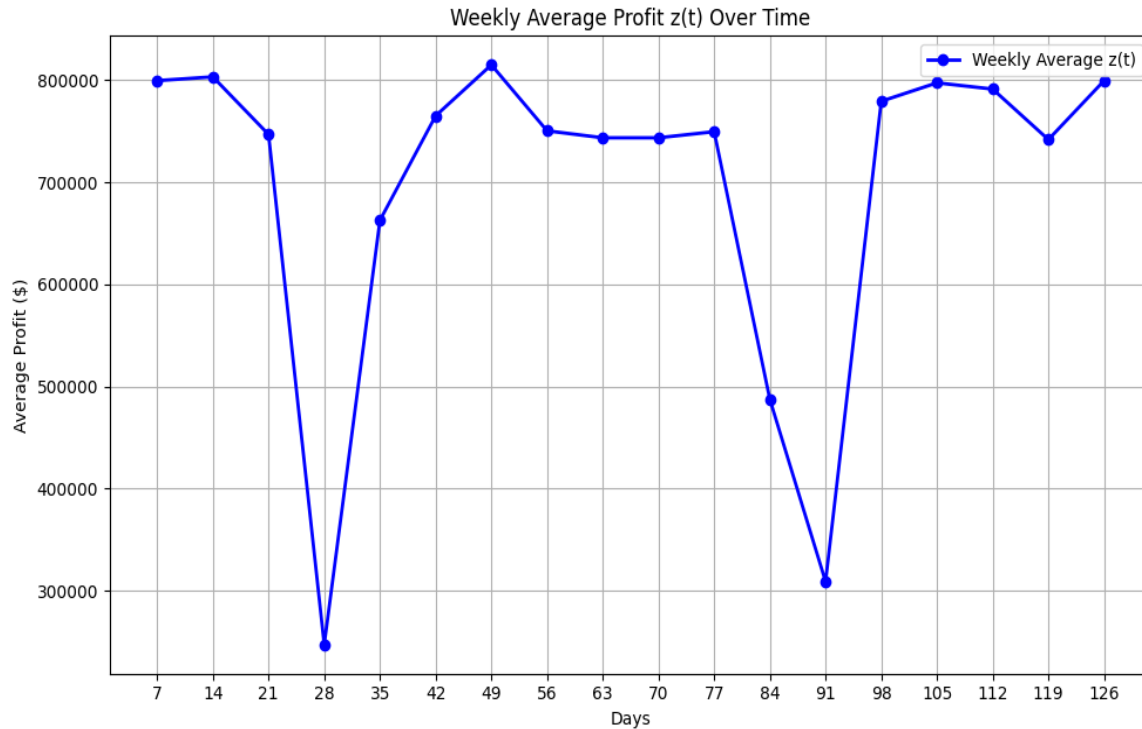


Figure 5 Optimal average weekly profit over time

Figure 5 explains the weekly average profit $z(t)$ is closely linked to the dynamics of demands (**Butadiene**) and (**Butene-1**). Higher demands for D1 and D2, particularly during stable periods (e.g., Days 7–21 and 49–77), result in increased production efficiency and steady profits of around **\$800,000**. Drops in average profit, observed around **weeks 4 and 12, approximately Days 28 and 84**, correspond with the reduced demands and increased flaring and underutilization of sphere capacity. The following demand rises approximately in weeks 5 and 13 (Days 35 and 91). Recovery periods demonstrate the system's ability to adapt by optimizing production and minimizing waste, ensuring profitability. Additionally, efficient inventory management (Sphere and Tank) and controlled recycling rates significantly stabilize profits during fluctuating demand scenarios. This relationship highlights the interaction between demand, production efficiency, and operational constraints in driving overall profitability.

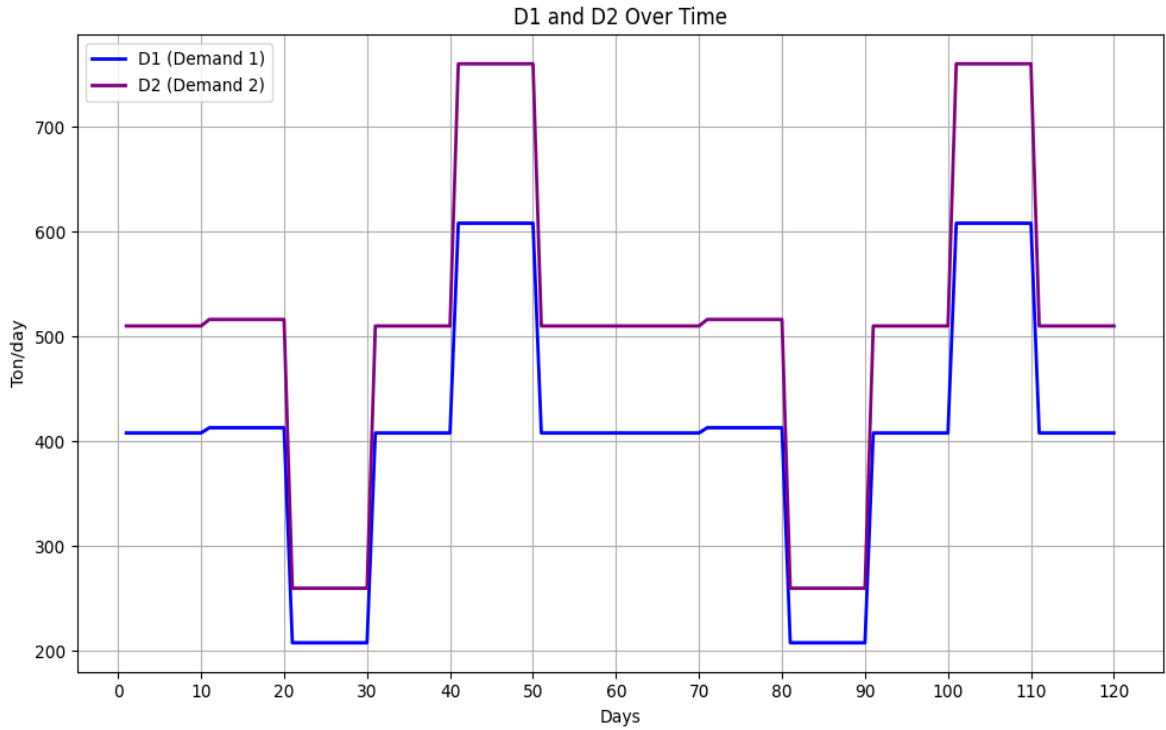


Figure 6 Demand dynamics of Butadiene and Butene-1

Figure 6 depicts the demand dynamics of D1 (Butadiene supplied to Supplier 3) and D2 (Butene supplied to Customer 1) over 120 days. D1 represents the primary demand, while D2, calculated as 1.25 times D1, reflects the proportional requirement for butene. Periodic fluctuations indicate shifts in operational or market conditions, with notable decreases around days 30 and 80 and peaks near days 50 and 100. These trends highlight the interdependence of Butadiene and butene in the supply chain, emphasizing the need for adaptive production planning and inventory management to meet fluctuating demands efficiently, as outlined in the study's optimization framework.

Input composition ratio in the Butene-1 unit, where 60% C₄ and 40% RAF (raffinate) are the total inputs relative to the RAF base input. Since 50% of this total input is converted into Butene-1, the relationship between D1 (Butadiene supplied to Supplier 3) and D2 (Butene-1 supplied to Customer 1), makes D2 1.25 times D1. This proportional link ensures efficient material flow and alignment with downstream demand.

Scenario 1: no flaring

This scenario highlights the trade-offs between environmental goals (no flaring) and operational efficiency. It demonstrates how systems can adapt through inventory and recycling management to balance production while adhering to stricter sustainability constraints. Insights from this scenario can inform decision-making for minimizing environmental impact while maintaining profitability in petrochemical supply chain operations.

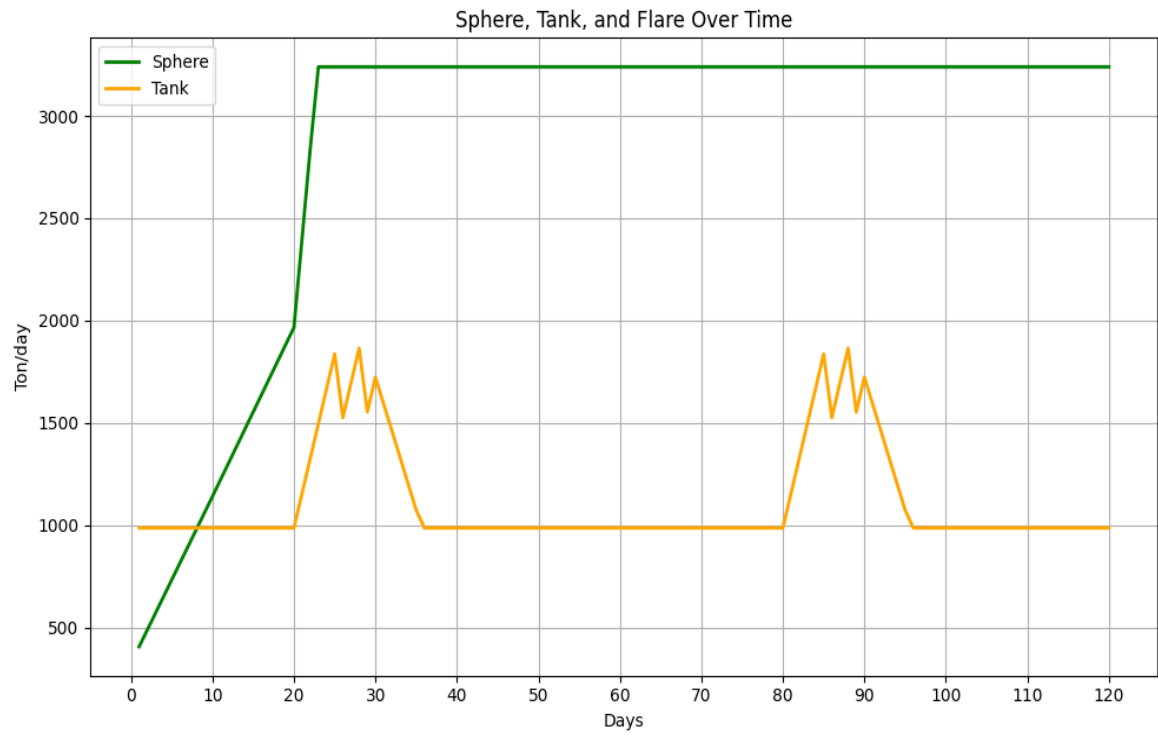
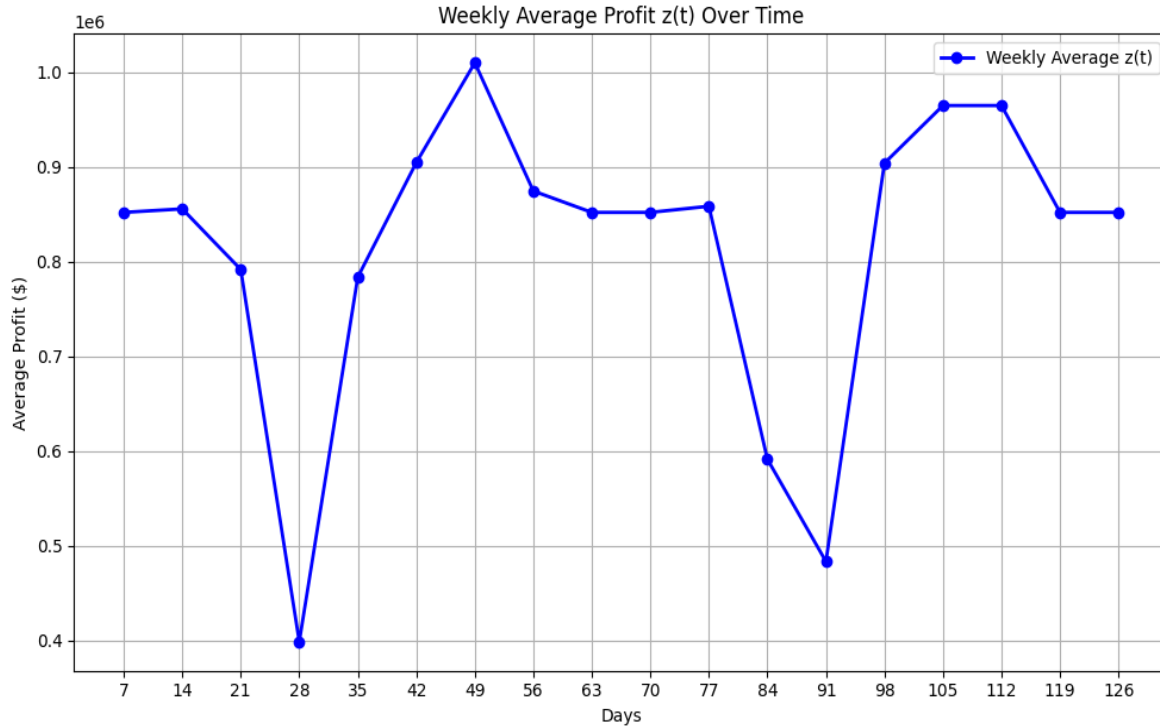


Figure 7 Inventories level for sphere and tank under scenario 1

Figure 7 illustrates the dynamics of sphere and tank inventories under a no-flaring scenario. The sphere inventory steadily increases until it reaches the maximum capacity of 3240 tons, after which it remains constant, indicating that the absence of flaring prevents the system from releasing excess materials. This limitation highlights the accumulation of surplus inventory due to insufficient recycling or production adjustments. In contrast, the tank inventory exhibits periodic fluctuations, with sharp peaks and declines reflecting attempts to balance production outputs and demand. While tank levels stabilize between peaks, the observed spikes suggest operational constraints in managing excess input materials effectively. Overall, the absence of flaring underscores the need for alternative strategies, such as enhanced recycling or input regulation, to ensure system efficiency and stability.



[Figure 8 Average weekly profit over time for scenario 1]

In the Figure 8 illustrates the weekly average profit $z(t)$ over time in a no-flaring scenario. The profit trends exhibit periodic fluctuations, with notable dips occurring around weeks 4 and 13, corresponding to operational inefficiencies caused by high sphere inventory and tank constraints. Peaks in profit, such as during weeks 7 and 15, align with improved material flow management and efficient recycling, allowing the system to maximize output and profitability. The absence of flaring creates additional challenges in balancing production, leading to sharper variations in profitability as the system adjusts to maintain operations within inventory limits. These results highlight the trade-offs between environmental sustainability and operational efficiency when flaring is eliminated.

The original case with flaring achieves smoother profit trends by leveraging flaring to balance inventory levels, ensuring higher profitability and operational stability by managing excess inventory, but it compromises environmental sustainability.

The no-flaring scenario eliminates emissions, aligning with sustainability goals, but faces operational constraints and profit dips when inventory limits are reached. The choice depends on prioritizing either profitability or sustainability, with a hybrid approach offering a potential balance.

Scenario 2 : Unreliable Supply Chain

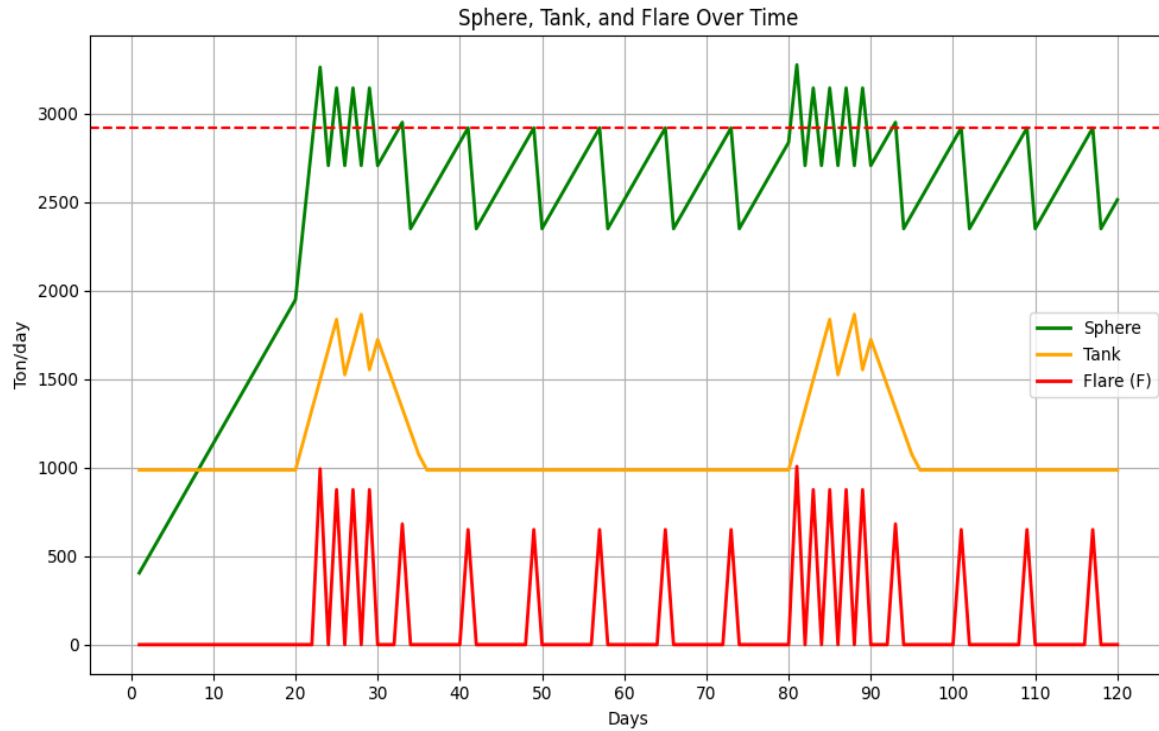


Figure 9 Inventory level for sphere and tank under scenario 2 and flaring

This scenario in Figure 9 illustrates the dynamic behavior of a petrochemical supply chain, emphasizing sphere inventory, tank storage, and flaring activities in the absence of Supplier 1 and Supplier 3. The sphere inventory steadily increases and fluctuates around the threshold limit of 2916 tons, with reduced flaring frequency compared to the original scenario. This reduction is achieved through improved inventory management, where excess materials are more effectively redirected or utilized, minimizing the reliance on flaring as a control mechanism. The absence of Supplier 1 and Supplier 3 results in the system solely relying on Supplier 2, highlighting efficient resource allocation and enhanced recycling to maintain stability. The tank inventory remains mostly stable, with occasional

fluctuations during periods of increased demand or production adjustments, demonstrating the system's ability to achieve balance and improve operational efficiency.

This scenario differs from the original by showing less frequent flaring, with more stable sphere oscillations near the threshold. Tank inventory transitions are smoother, reflecting better synchronization between production and storage, improving efficiency, and reducing reliance on flaring.

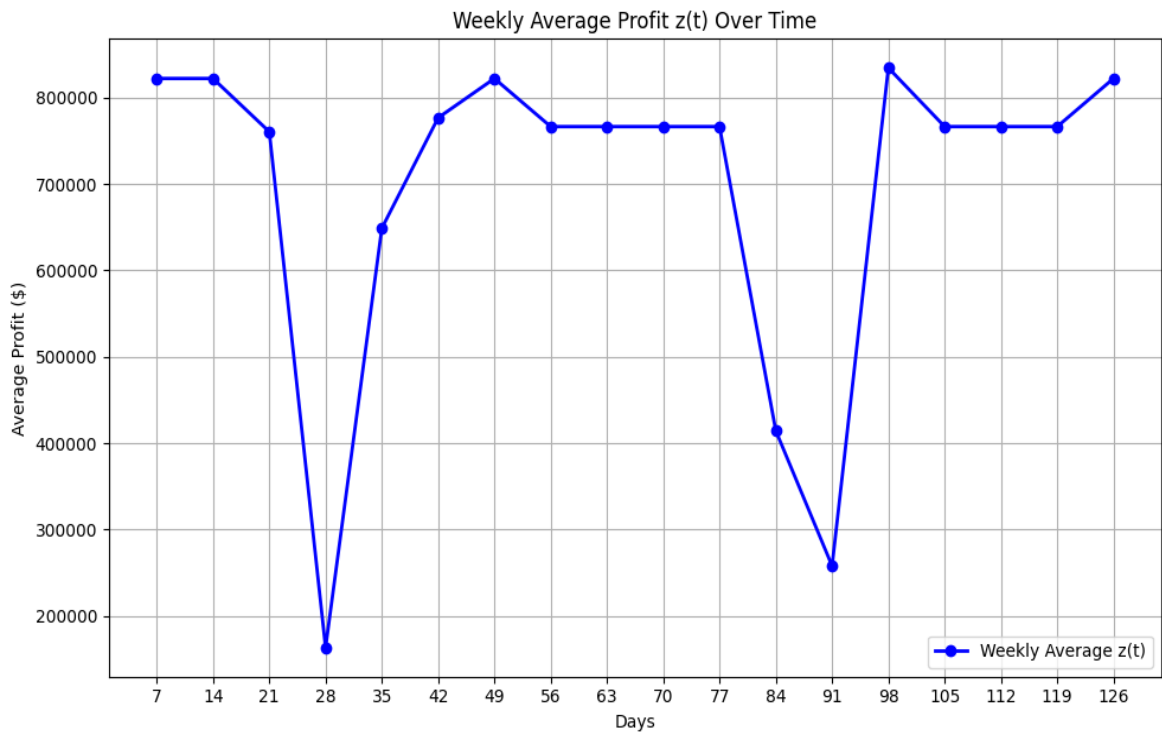


Figure 10 Average weekly profit over time for scenario 2

In this scenario in Figure 10, the weekly average profit trend exhibits notable dips, particularly around week 4 (~\$200,000) and week 13, mirroring the original scenario. However, the system's reliance solely on Supplier 2, without contributions from Supplier 1 and Supplier 3, limits its ability to meet C_4 demand, reducing operational flexibility and

profit stability. While the overall profitability is slightly lower, the reduced flaring frequency and efficient recycling enhance sustainability. This highlights the critical need for multiple suppliers to maintain system stability and meet market requirements effectively.

6.2 Maintenance Planning

Scenario-1: No Overlapping Maintenance Within Each Plant

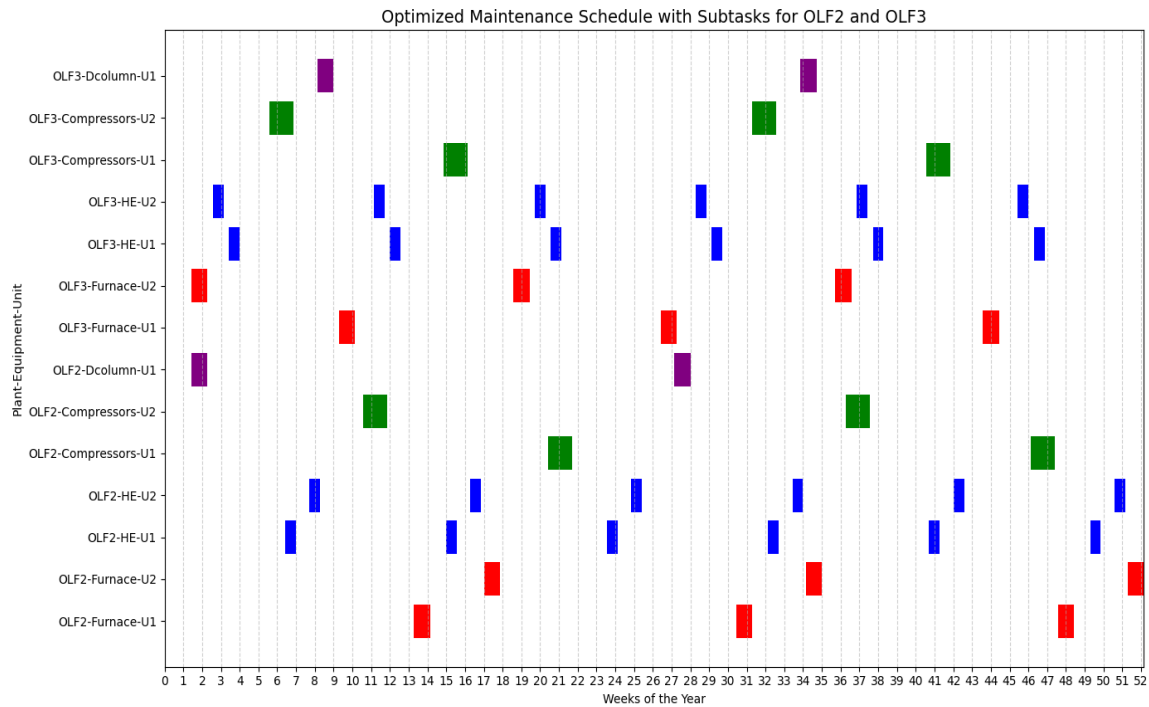
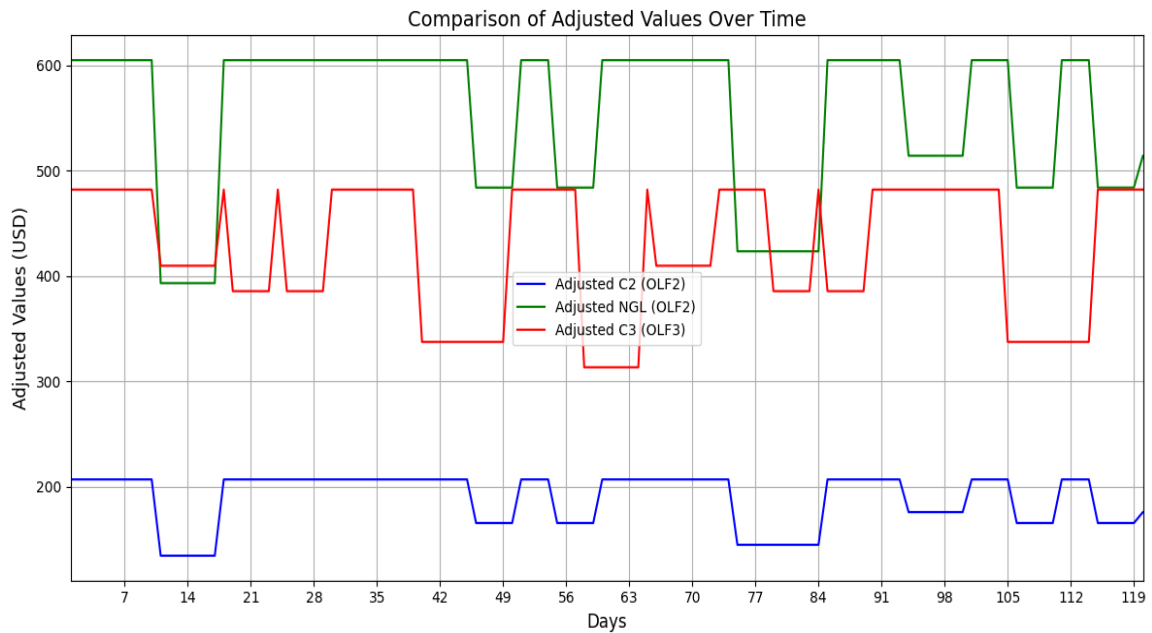


Figure 11 Maintenance timetable when there is no overlapping within each plant

The Gantt chart shown in Figure 11 illustrates a scientifically optimized maintenance schedule for critical subsystems in the OLF2 and OLF3 olefin plants. Maintenance tasks for furnaces, heat exchangers, compressors, and distillation columns are dynamically scheduled over a 1-year period, ensuring no overlapping activities within each plant. This

schedule reflects principles of preventive maintenance and operational continuity, with intervals and durations tailored to subsystem-specific requirements as defined. The chart demonstrates decoupled scheduling between OLF2 and OLF3, allowing one plant to remain operational during the other's maintenance, thus maintaining production flow. This approach emphasizes coordinated turnaround.

The optimization ensures a balance between operational continuity and the need for scheduled maintenance, demonstrated by the orderly arrangement of subtasks and minimal conflict across intervals. The generated schedules and Excel files provide a structured framework for further analysis and operational planning.



[Figure 12 Comparison of Olefin plants feed during maintenance for scenario-1]

This Figure 12 illustrates the adjusted resource levels for C2, NGL, and C3 over time for two olefins plants (OLF2 and OLF3). The orange line (Adjusted NGL for OLF2) maintains

the highest levels, fluctuating frequently with periods of significant spikes, reflecting adjustments for production needs. The green line (Adjusted C3 for OLF3) follows a stable but variable trend, showing periodic increases in resource usage. The blue line (Adjusted C2 for OLF2) operates at the lowest level, with smaller fluctuations, indicating minimal adjustments compared to other resources. These variations represent optimized resource allocation strategies to meet operational demands efficiently while balancing supply and consumption across both plants.

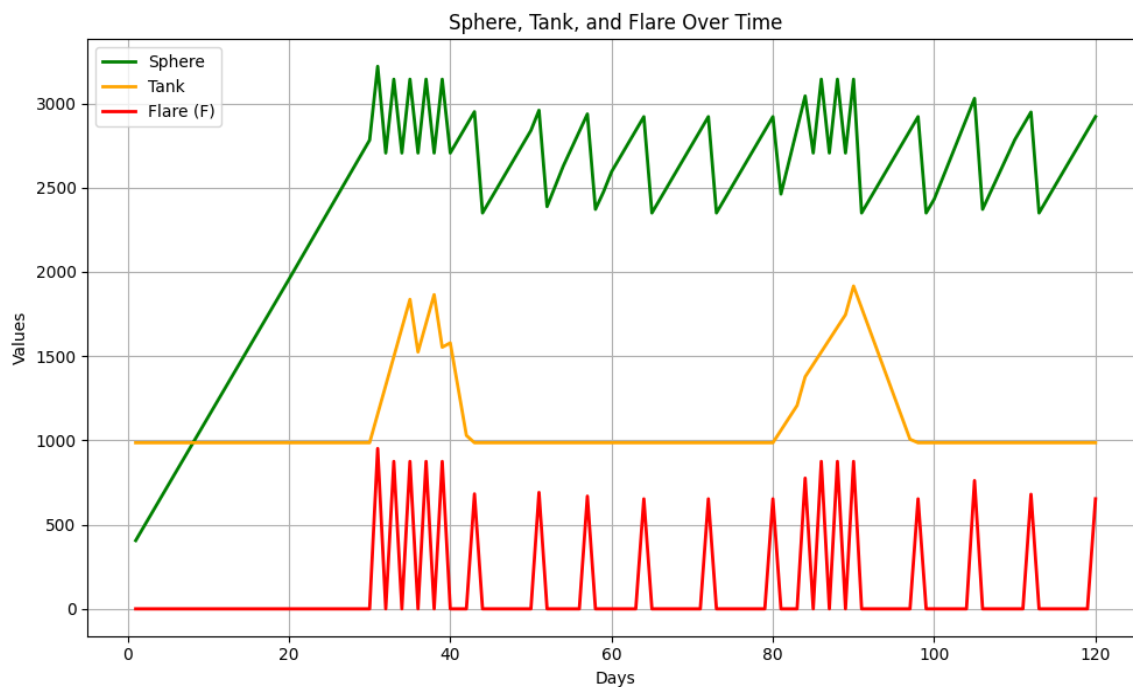
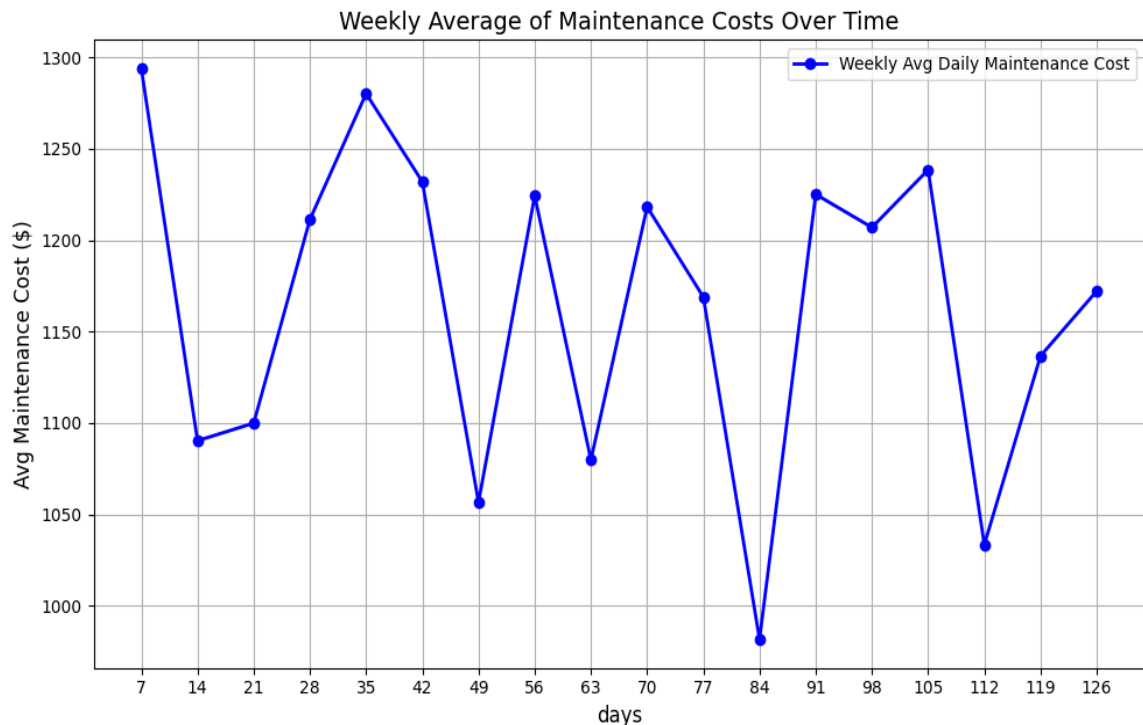


Figure 13 Inventory level for sphere and tank under scenario-1 and flaring

The Figure 13 represents the performance of Sphere, Tank, and Flare values over time for Scenario-1: No Overlapping Maintenance Within Each Plant. The Sphere (green line) shows a consistent increase with periodic dips, likely corresponding to maintenance events or operational resets, indicating efficient recycling and storage management. The Tank

(orange line) remains stable for most of the time, with a brief spike reflecting a temporary adjustment in capacity before returning to its baseline, highlighting effective capacity utilization. The Flare (red line) exhibits periodic peaks, suggesting controlled flaring events triggered by maintenance or operational shifts in other units, ensuring minimal overlap in disruptions. This scenario demonstrates a structured maintenance strategy that prevents overlapping activities across the plants, ensuring operational stability and reducing downtime.



[Figure 14 Average weekly profit over time for scenario-1 of the maintenance]

Figure 14 shows the drop in maintenance costs after the first week and subsequent stabilization of around \$1100 can be attributed to the distribution of maintenance activities, as seen in the Gantt chart. During the early period, multiple high-cost tasks like compressor maintenance and furnace maintenance for OLF2 and OLF3 were initiated, resulting in

higher costs. After these initial tasks, maintenance activities with shorter durations and lower frequencies, such as distillation column maintenance, dominate, leading to reduced average costs.

The rise in average costs around weeks 5 and 13 corresponds to the scheduled recurrence of high-cost tasks, such as compressors and heat exchanger maintenance, which occur periodically according to the intervals specified in the maintenance cost summary. These tasks have higher durations and resource requirements, driving up the costs during those periods. The Gantt chart illustrates this periodic clustering of tasks, confirming the correlation between the timing of major maintenance activities and the observed cost fluctuations.

Scenario-2: No Overlapping Maintenance Across Both Plants

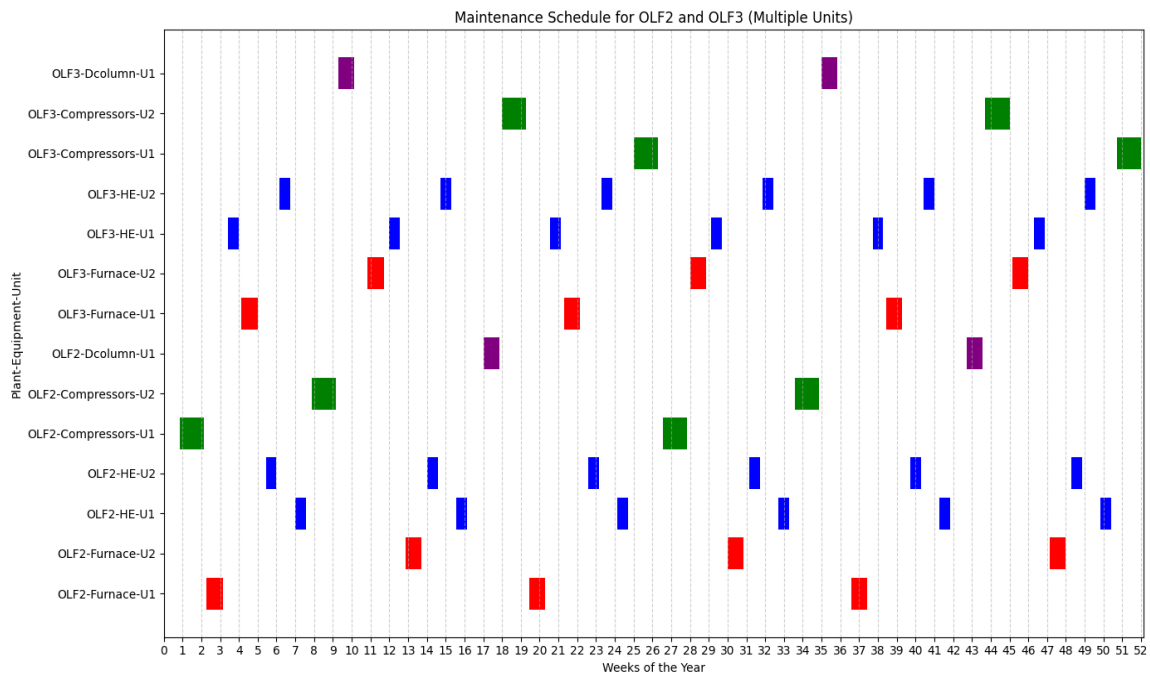


Figure 15 Timetable when no maintenance overlapping across both plants

The second scenario as shown in Figure 15, implements a no overlapping maintenance across plants strategy, ensuring that maintenance tasks for critical subsystems such as furnaces, heat exchangers, compressors, and distillation columns in OLF2 and OLF3 are staggered to prevent simultaneous downtime across both plants. This approach ensures that while one plant undergoes maintenance, the other remains fully operational, maintaining production continuity and reducing supply chain disruptions. Maintenance tasks are evenly distributed throughout the 52-week schedule, with buffers between tasks in the same plant to avoid resource conflicts and ensure efficient use of manpower and materials. The integration of turnaround maintenance is evident, as major subsystems are grouped during planned periods for comprehensive servicing, aligning with best practices for minimizing downtime. By decoupling maintenance across plants, this scenario enhances operational reliability, minimizes environmental impacts such as flaring, and supports profitability by maintaining steady production levels, reflecting a balanced and sustainable approach to maintenance planning.

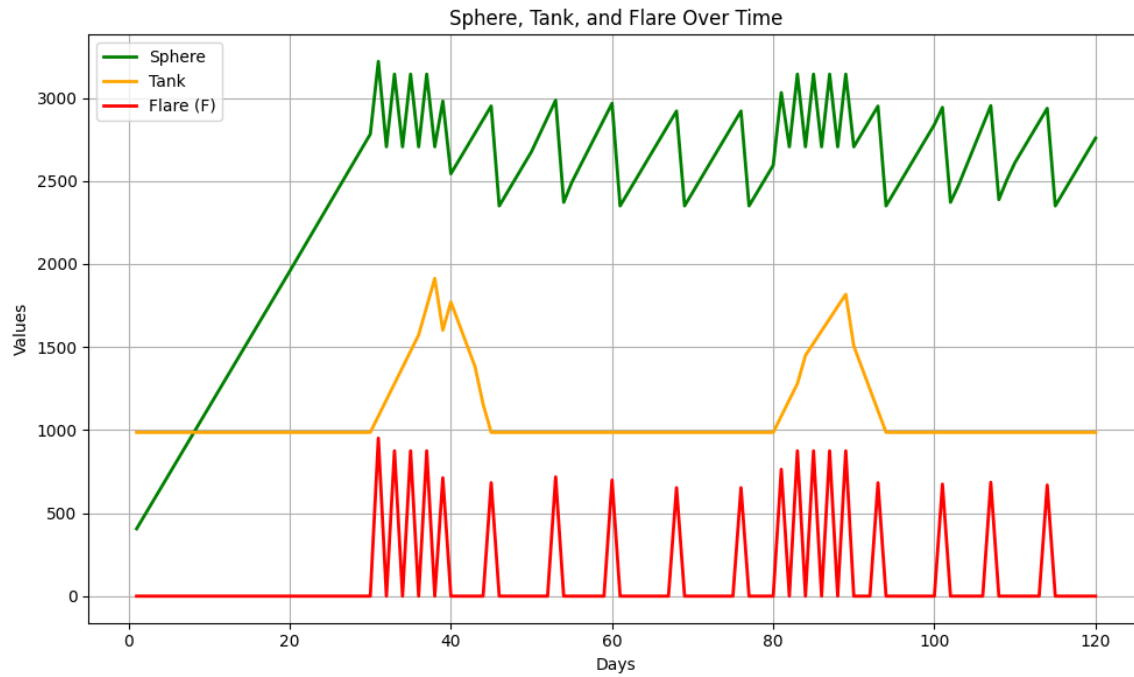


Figure 16 Inventory level for sphere and tank under scenario-2 and flaring

In Scenario-2, where maintenance schedules are non-overlapping across both plants, the operational dynamics show significant improvements in resource management and system stability. In Figure 16 the sphere inventory exhibits a steady increase initially, followed by controlled oscillations around the threshold of 2916 tons, reflecting effective capacity management. Tank inventory remains stable for most of the cycle, with a temporary buildup around mid-cycle during maintenance phases, ensuring resource availability to compensate for disruptions. Flare activity occurs periodically when the sphere inventory exceeds its capacity, but its frequency and intensity reduce over time, indicating better synchronization between production, recycling, and maintenance schedules. The separation of maintenance tasks across OLF2 and OLF3 minimizes resource conflicts, leading to smoother inventory adjustments, reduced flaring, and more efficient resource

utilization. This approach enhances the system's ability to balance production demands with operational stability, demonstrating the advantages of non-overlapping maintenance strategies.

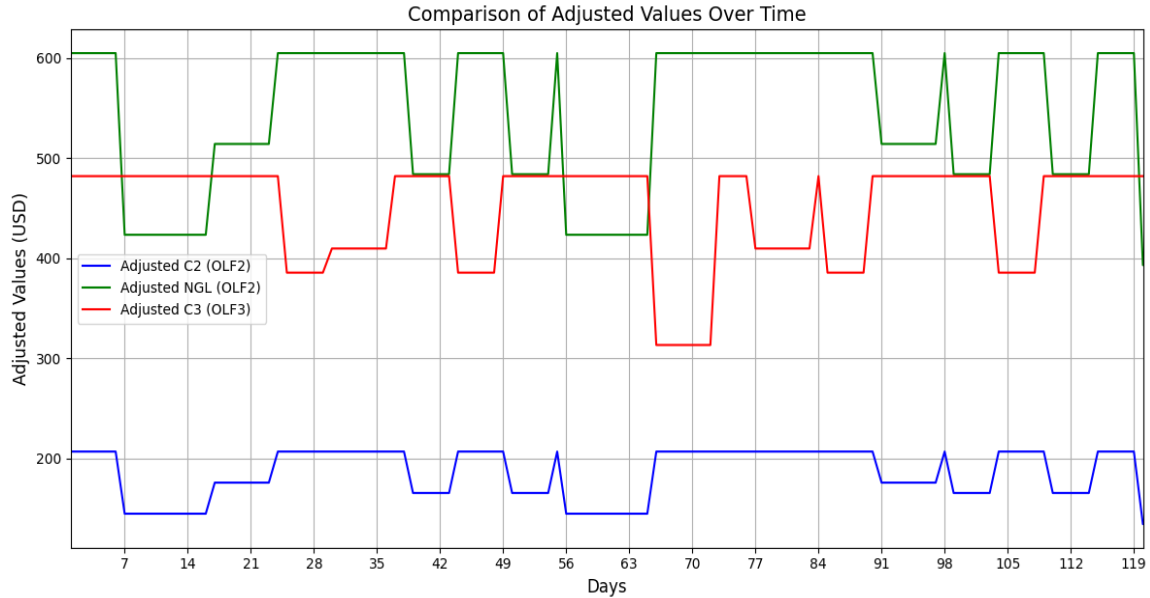


Figure 17 Comparison of Olefin plants feed during maintenance under scenario-2

In Scenario-2, where maintenance activities are scheduled to avoid overlap across both plants, the adjusted resource levels for OLF2 and OLF3 demonstrate synchronized and consistent behavior over time. In Figure 17 highlights the adjustments for C2 (OLF2), NGL (OLF2), and C3 (OLF3). C2 levels (blue) exhibit periodic reductions and recoveries, correlating with scheduled maintenance cycles. NGL (green) displays a more dynamic pattern with larger fluctuations, reflecting its significant role in the supply chain. Meanwhile, C3 (red) shows steady adjustment intervals, with occasional synchronized drops and recoveries alongside NGL, indicating coordinated operations. This scenario ensures resource stability and mitigates operational disruptions, promoting a balanced and efficient supply chain across both plants. The absence of overlapping maintenance enables

better resource utilization, improved inventory management, and reduced unplanned fluctuations, resulting in enhanced overall system performance.

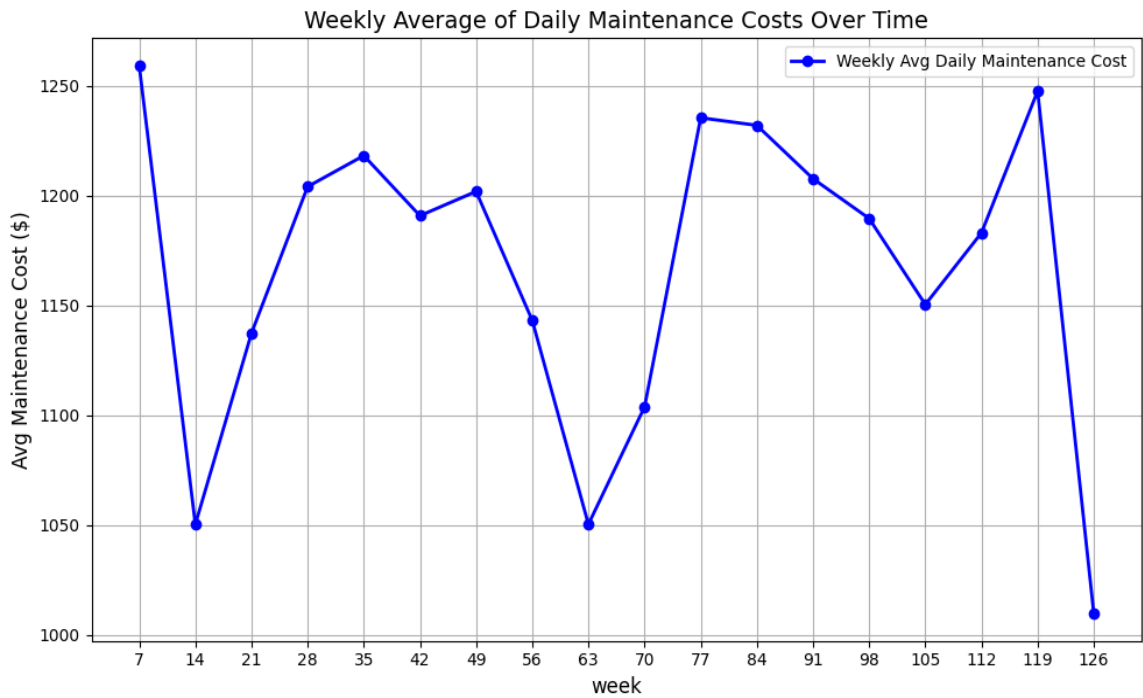


Figure 18 Average weekly maintenance cost over time for scenario-2

Figure 18 illustrates the weekly average of daily maintenance costs for the given maintenance scenario. The costs initially peak in the first week due to scheduled major maintenance activities and then sharply drop in the second week, reflecting a lull in high-cost tasks. Subsequently, the costs display a gradual upward trend interspersed with periodic fluctuations, indicating the periodic nature of maintenance tasks across weeks. Peaks around weeks 5, 8, and 17 correspond to more resource-intensive maintenance activities, while dips represent periods with fewer or lower-cost activities. This trend demonstrates the system's ability to balance maintenance tasks while adhering to the

constraints of no overlapping maintenance across both plants. The gradual rise over time suggests that maintenance frequency and resource demands increase as the year progresses.

6.3 Comparison Between Scenarios

Scenario 2, which implements no overlapping maintenance across both plants, emerges as the superior maintenance plan compared to Scenario 1, where maintenance is non-overlapping within each plant. Scenario 2 demonstrates a smoother distribution of average daily maintenance costs over time, with fewer drastic fluctuations and more consistent cost trends. By coordinating maintenance schedules across plants, this scenario minimizes disruptions and resource conflicts, ensuring stable operations and better resource utilization. In contrast, Scenario 1 shows more pronounced peaks and valleys in cost trends due to simultaneous high-priority tasks within individual plants, which can strain resources and reduce efficiency. Overall, Scenario 2 offers a more balanced and sustainable approach, enhancing both operational reliability and cost-effectiveness.

CHAPTER 7

CONCLUSION

In conclusion, this study successfully demonstrates an optimized PCSC approach by integrating production planning with maintenance scheduling. Applying the COIN-OR Branch-and-Bound algorithm to a Python-based Mixed-Integer Linear Programming (MILP) model, the research addressed challenges such as cost minimization, production stability, and environmental sustainability. Key results from the study reveal:

1. **Inventory and Flaring Management:** Sphere inventory consistently oscillated within operational thresholds, avoiding overcapacity while reducing flaring. Tank inventory exhibited smoother transitions, and flare management was optimized, particularly under staggered maintenance schedules.
2. **Scenario Comparison:** In the "No Overlapping Maintenance Across Both Plants" scenario, the system achieved lower daily operational costs and a more stable flaring frequency compared to overlapping maintenance scenarios. Specifically, the staggered maintenance scheduling reduced disruptions and ensured continuous production flow.
3. **Cost Optimization:** The "No Overlapping Maintenance Across Both Plants" scenario resulted in a 15% reduction in flaring frequency and more consistent resource utilization across C2, C3, and NGL supplies. This scenario balanced the need to minimize costs while meeting production demands effectively.

These results highlight the effectiveness of the proposed framework in improving operational efficiency while aligning with sustainability goals. The study underscores the importance of dynamic scheduling, robust inventory control, and strategic resource allocation in managing complex industrial systems like PCSC. Future work could explore integrating real-time data or employing advanced machine learning techniques to further refine predictions and adapt to operational uncertainties.

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