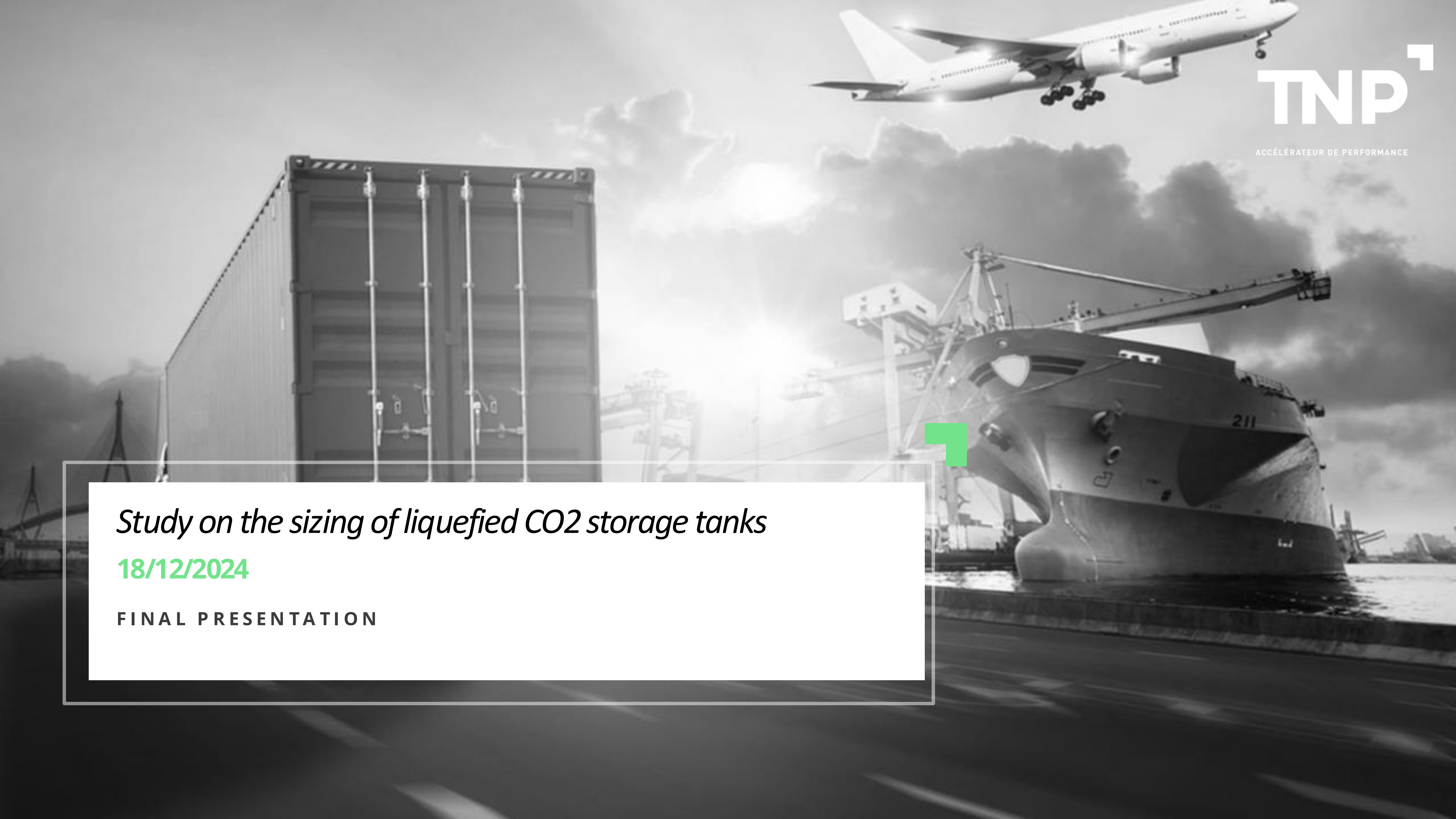


TNP

ACCÉLÉRATEUR DE PERFORMANCE

Study on the sizing of liquefied CO2 storage tanks

18/12/2024

FINAL PRESENTATION

OBJECTIVES OF THE MODELING

01

Optimize the management of ship rotations to **minimize delays** and **costs**

02

Anticipate waiting periods or interruptions caused by logistical, meteorological, or maintenance constraints

03

Identify critical scenarios and provide recommendations to improve the efficiency of the CO_2 maritime transport system

METHODOLOGY FOLLOWED

The following methodology outlines the tools, simulation setup, and key entities involved in modeling and optimizing CO_2 transport and storage processes.

Tools Used

- → Python with **SimPy** for stochastic process modeling.
- → Analysis of **logistical** and **meteorological** constraints.

Simulation Entities

- → **Ports:** Loading and unloading hubs with capacity constraints.
- → **Ships:** Transport units with specific capacities and transit times.
- → **Factories:** CO_2 production or recycling facilities.
- → **Storage Tanks:** Temporary holding units for CO_2 with limited capacities.

Simulation Description

- → **Objective:** Model and optimized CO2 transport and storage logistics .
- → **Key Features:** Simulated flows between ports , factories , ships and storage tanks.
- → **Key Variables:** Time tracking for operations (loading , unloading , transit , etc,).
- → **Time scale:** Period of 1h / Day ...

SIMULATOR DESIGN FUNCTIONNAL SPECIFITIONS

This functional design outlines the process for running CO_2 logistics simulations, from input configuration to automated results generation, ensuring clear and customizable workflows for users.

→ Reference data provided by the user

→ Scenario to simulate defined within the **YAML file**

→ Direct editing of input data in the YAML file to customize scenarios

YAML file loaded into the module 02

→ The **.exe program** runs the simulation based on the YAML configuration.

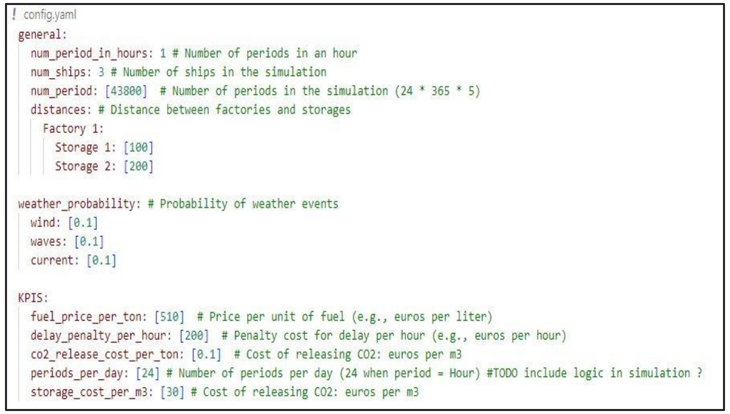
→ Automated processing of input data to generate results

Automatically generated results 03

→ Results are available as **graphs and Excel files.**

→ Users can access results via a dedicated webpage.

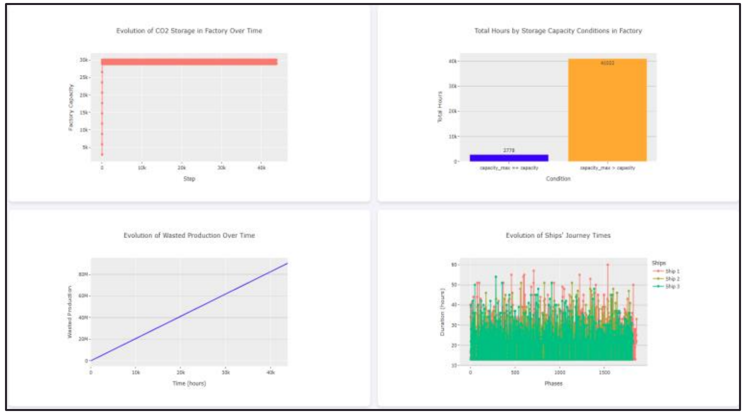
→ Exportable data for further analysis.



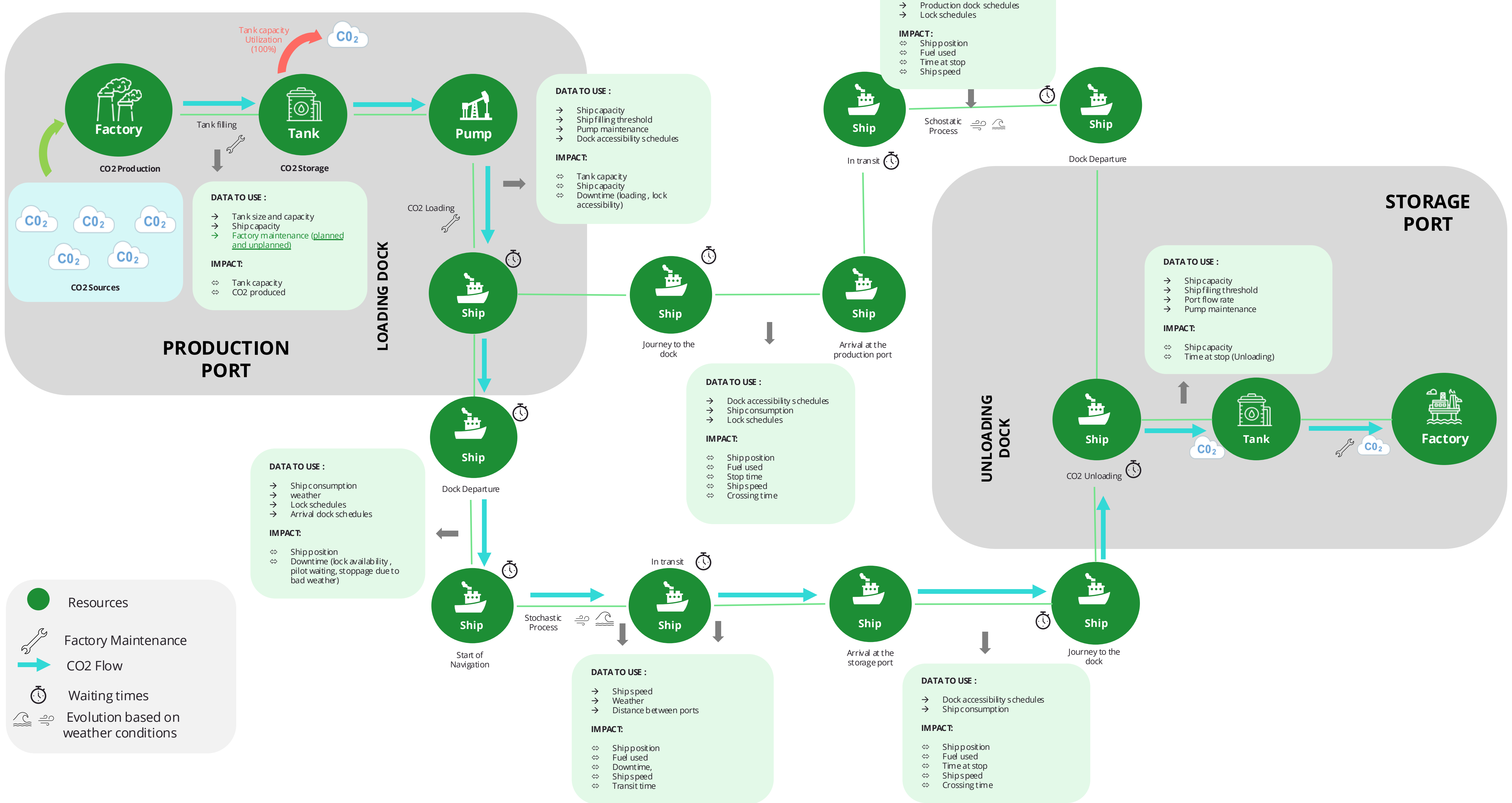
```yaml
! config.yaml
general:
  num_period_in_hours: 1 # Number of periods in an hour
  num_ships: 3 # Number of ships in the simulation
  num_period: [43800]  # Number of periods in the simulation (24 * 365 * 5)
  distances: # Distance between factories and storages
    Factory 1:
      Storage 1: [100]
      Storage 2: [200]

weather_probability: # Probability of weather events
  wind: [0.1]
  waves: [0.1]
  current: [0.1]

KPIS:
  fuel_price_per_ton: [510]  # Price per unit of fuel (e.g., euros per liter)
  delay_penalty_per_hour: [200]  # Penalty cost for delay per hour (e.g., euros per hour)
  co2_release_cost_per_ton: [0.1]  # Cost of releasing CO2: euros per m3
  periods_per_day: [24] # Number of periods per day (24 when period = Hour) #TODO include logic in simulation ?
  storage_cost_per_m3: [30] # Cost of releasing CO2: euros per m3
```

configurable_main.exe	02/12/2024 16:10	Application	75 831 Ko
config.yaml	28/11/2024 13:26	Fichier source Yaml	4 Ko

Nom	Modifié le	Type	Taille
Graphs data.xlsx	02/12/2024 16:00	Feuille de calcul Micros...	2 468 Ko
Graphs gallery.html	02/12/2024 16:00	Chrome HTML Docume...	33 388 Ko



DATA MODEL OF THE APPLICATION



CONFIGURATION OF MODEL VARIABLES

TANK VARIABLES	TYPES	VALUES
Capacity of the tank	Continuous	4000 – 9000 m^3 → Depends on the scenarios.
Maintenance of the factory (Scheduled)	Set time intervals	Maintenance is scheduled for 3 weeks every 6 years, which averages out to 1.5 weeks per year
Maintenance of the factory (Unscheduled)	Probability	1.5 weeks with a probability of XX% annually/daily/monthly
Impact of maintenance	Continuous	-1% / -0.5%
Production capacity (annual)	Continuous	Depends on the scenarios.

DOCK VARIABLES (Arrival + Departure)	TYPES	VALUES
Capacity of the dock	Continuous	Depends on the scenarios.
Waiting Times	Continuous /Probability	*Time for loading and unloading, waiting for weather, waiting for pilot (2 hours), waiting for dock availability, waiting for lock, waiting for maintenance*
Accessibility of locks	Continuous time periods	24 hours a day, 7 days a week
Maintenance	Continuous Probability	Depends on the scenarios

WEATHER VARIABLES	TYPES	VALUES
Wind	Probability	- Wind > 55 kn: 0% - Wind < 55 kn: → Waves < 4m : 94,49% → 4m < Waves < 6m : 4,850% → 6m < Waves < 9m : 0,650% → Waves > 9m : 0,010%
Height of waves	Probability	

SHIPS VARIABLES	TYPES	VALUES
Capacity of the ship	Continuous	- Maximum usage rate : 90% - 12.000 - 18.000 - 20.000 m^3
Threshold for filling the tank	Continuous	100% - XX% Depends on the scenarios
Fuel consumption	Continuous	To be determined
Ship speeds (Depends on weather conditions)	Continuous	12 kn + acceleration or deceleration (depending on stopping times and weather conditions)
Distance traveled	Continuous	- Port of Rotterdam (NL) : 263 nm - Port of Bergen (NO) : 739 nm

TECHNICAL CONSIDERATION OF THE MODEL

This section outlines the critical performance metrics tracked in the model and highlights the current limitations that may impact the accuracy and robustness of the results.

Key Metrics Tracked

- **Loading/Unloading Times:** Average and maximum durations for operations at ports.

- **Ship Utilization Rates:** Percentage of time ships are active.

- **Storage Tank Fill Levels**: Monitoring of CO_2 storage usage to avoid overflow or underutilization.

Limitations

- **Weather conditions:** Challenging to fully anticipate or integrate unpredictable weather patterns.

- **Maintenance:** Includes several unpredictable maintenance events that are difficult to forecast.

- **Accidents and blockages:** Disruptions caused by unforeseen incidents are not currently modeled.

- **Random events:** Stochastic variations in key parameters are limited and could be expanded.

MAIN EXPLANATIONS FOR RESULTS

This section highlights the key performance indicators (KPIs) used to analyze the system's efficiency and provides specific insights into the impact of constraints and scenarios on the results.

- **Global Results :** Presentation of the results compared to the initially planned output KPIs to evaluate system performance and efficiency.

KPI	DESCRIPTION
CO_2 Storage Evolution	Tracking variations in CO_2 storage levels in tanks over time.
Ship Travel Time	Duration of trips made by ships between production and storage ports.
Ship Waiting Time	Time during which ships are at a standstill, either waiting for dock access or awaiting operations.
CO_2 Released Quantities	Volume of CO_2 released during production or maintenance processes.
CO_2 Transported Quantities	Total amount of CO_2 transported by ships over a given period.
Stock Saturation Periods	Duration during which CO_2 stocks reach their maximum capacity, preventing any additional production.
Stock Empty Periods	Time during which CO_2 stocks are empty or underutilized, affecting operational continuity.
Cost Sensitivity Analysis Based on Storage Size	Study of the impact of variations in tank sizes on operational costs.
Cost Sensitivity Analysis Based on Ship Size	Analysis of the impact of different ship sizes used for CO_2 transport on costs.

- **Specific Results:** Identification of the impacts of different configurations and constraints on the system's overall performance through various scenarios:
  - **Meteorological Constraints :** With weather constraints / Without weather constraints.
  - **Maintenance Schedules:** With schedules maintenance / Without schedules maintenance.
  - **Port Scenarios:** From a specific departure port to a defined arrival port.
- **Visualizations :** Graphs and visual outputs are generated to facilitate the interpretation of results and comparisons across scenarios.

INTERACTIVE DEMO: REAL-TIME RESULTS

The purpose of the demo is to highlight the flexibility and usability of the model and to facilitate decision-making with clear and interactive visualizations.

01

Interactive Parameter Adjustment

Demonstrate how users can dynamically modify the input parameters of the simulation.

→ **Modifiable Parameters:**

- Tank capacity
- Capacity of production
- Ship speed
- Meteorological constraints
- Maintenance schedules….

02

Results Visualization

→ **Real-time Graphs:** Results are automatically updated and displayed on the **Streamlit interface.**

→ **Key Visual Outputs**:

- CO_2 storage evolution over time
- Ship travel and waiting times
- Stock saturation and empty periods

03

Scenario Comparisons

Easily observe the impact of parameter changes on system performance.

MAIN EXPLANATIONS FOR RESULTS

→ **4 phases** were analyzed, each corresponding to an increasing annual capacity.

→ For each phase, **2 destinations** were considered:

- Rotterdam: 263 nm
- Bergen: 739 nm

→ This resulted in a total of **8 scenarios.**

→ These scenarios explored:

- Variations in ship capacity.
- Variations in storage availability.

Overview of the 8 Scenarios Considered for CO_2 Transport :

Destination / Annual Capacity	Phase 1.a 530 ktpa	Phase 1.b 1.200 ktpa	Phase 2 2.400 ktpa	Phase 3 3.000 ktpa
Rotterdam (NL) 263 nm	Ships: 12kt; Storage: 18kt Ships: 18kt; Storage: 27kt	Ships: 18kt; Storage: 27kt	Ships: 18kt; Storage: 27kt	Ships: 18kt; Storage: 27kt
Bergen (NO) 739 nm	Ships: 18kt; Storage: 27kt	Ships: 18kt; Storage: 27kt	Ships: 18kt; Storage: 27kt	Ships: 18kt; Storage: 27kt

TNP

HARNESS THE UNPREDICTABLE

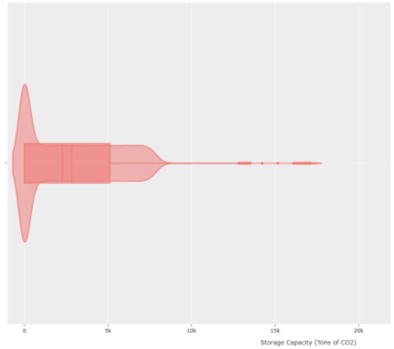
Phase 1.a : 530 ktpa

PHASE 1a : 530 ktpa (BERGEN)

Bergen 12k :

Parameter	Value
Annual production	530ktpa
Storage	18kt
Ships	12kt
Number of ships	1

→ Tank usage Violin Plot



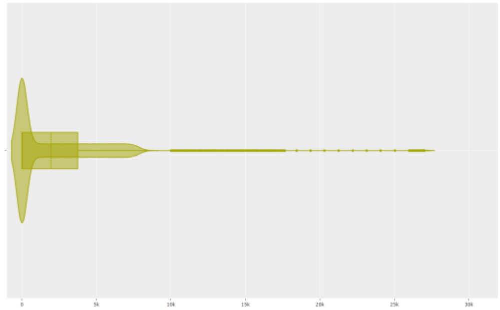
→ Kpis

Parameter	Value
Tank Cost	67,320,000.0€
Fuel Cost	11,502,200.0
CO2 Storage Cost	89,915,000.0€
Release CO2 Cost	686,027.4€
Total Cost	304,923,227.4€

Bergen 18k:

Parameter	Value
Annual production	530ktpa
Storage	27kt
Ships	18kt
Number of ships	1

→ Tank usage Violin Plot



→ Kpis

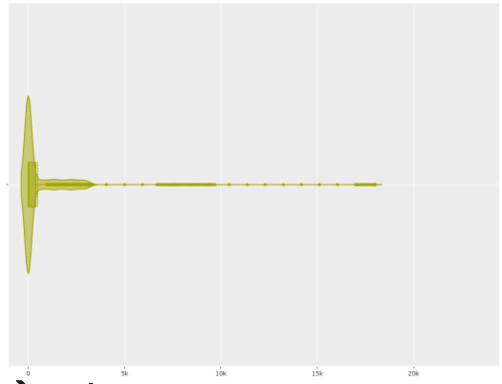
Parameter	Value
Tank Cost	100,680,000.0€
Fuel Cost	7,711,200.0€
CO2 Storage Cost	90,125,000.0€
Release CO2 Cost	683,424.66€
Total Cost	334,699,624.66€

PHASE 1a : 530 ktpa (Rotterdam)

Rotterdam 12k :

Parameter	Value
Annual production	530ktpa
Storage	18kt
Ships	12kt
Number of ships	1

→ Tank usage Violin Plot



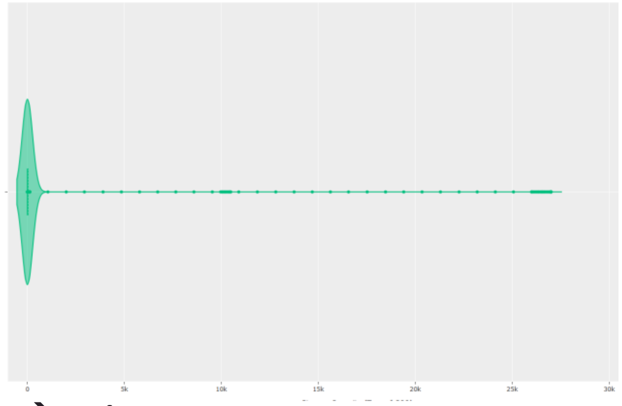
→ Kpis

Parameter	Value
Tank Cost	67,320,000.0€
Fuel Cost	4,203,250.0€
CO2 Storage Cost	89,915,000.0€
Release CO2 Cost	231,849.32€
Total Cost	261,670,099.32€

Rotterdam 18k:

Parameter	Value
Annual production	530ktpa
Storage	27kt
Ships	18kt
Number of ships	1

→ Tank usage Violin Plot



→ Kpis

Parameter	Value
Tank Cost	100,680,000.0€
Fuel Cost	2,815,200.0€
CO2 Storage Cost	90,125,000.0€
Release CO2 Cost	225,342.47€
Total Cost	329,345,542.47€

PHASE 1a : 530 ktpa (ROTTERDAM / BERGEN)

Analysis:

- For both phase 1a it seems that 1 boat is enough to handle the production load.
- The limitating factor being the production, it is normal that the deposited amount doesn't change even if the boats are bigger
- The reduced fuel cost between 12k boats and 18k boats is because the boats travel less when they are bigger
- The increase in total cost is due to the extra tank being built and a bigger boat being bought

TNP

HARNESS THE UNPREDICTABLE

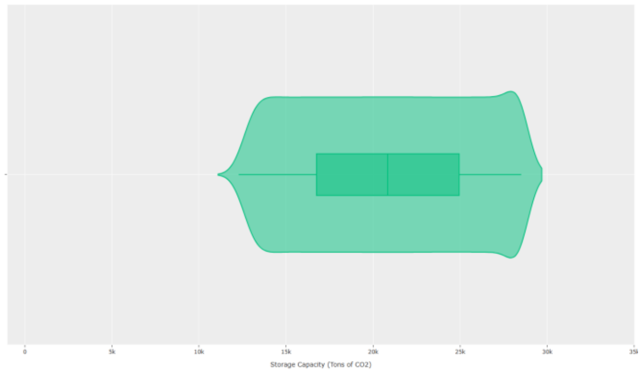
Phase 1.b : 1.200 ktpa

PHASE 1b : 1,200 ktpa (Rotterdam/Bergen)

Bergen 18k :

Parameter	Value
Annual production	1200ktpa
Storage	27kt
Ships	18kt
Number of ships	1

→ Tank usage Violin Plot



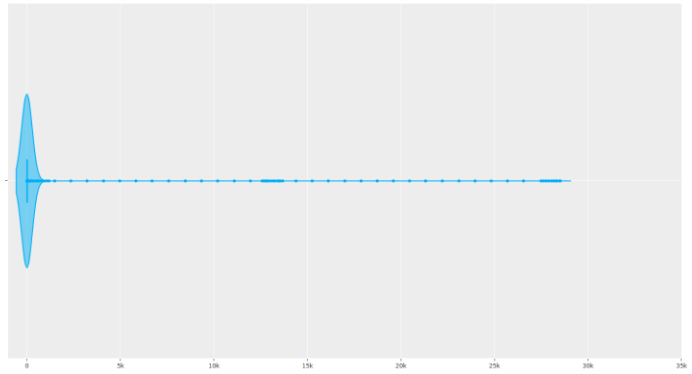
→ Kpis

Parameter	Value
Tank Cost	100,680,000.0€
Fuel Cost	15,432,600.0€
CO2 Storage Cost	180,845,000€
Release CO2 Cost	23,127,397.26€
Total Cost	455,584,997.26€

Rotterdam 18k:

Parameter	Value
Annual production	1200ktpa
Storage	27kt
Ships	18kt
Number of ships	1

→ Tank usage Violin Plot



→ Kpis

Parameter	Value
Tank Cost	100,680,000.0€
Fuel Cost	5,901,975.0€
CO2 Storage Cost	189,665,000.0€
Release CO2 Cost	590,410.96€
Total Cost	432,337,385.96€

PHASE 1b : 1.200 ktpa (ROTTERDAM / BERGEN)

Analysis:

- In the Bergen scenario, we can see that the tanks starts to reach their limits, but the total cost of 23 millions paid in taxes for releasing the CO_2 doesn't justify buying an extra boat
- In the Rotterdam scenarion we can see that with just one boat, the production is not enough to keep the boat busy all the time, thus the reduced cost in fuel compared to the bergen scenario

TNP

HARNESS THE UNPREDICTABLE

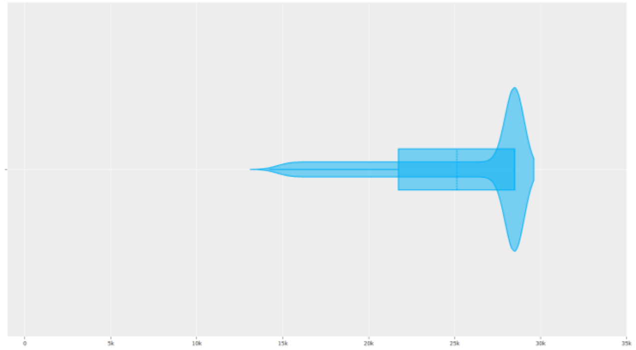
Phase 2 : 2.400 ktpa

PHASE 2 : 2,400 ktpa (Rotterdam/Bergen)

Bergen 1 ship :

Parameter	Value
Annual production	2400ktpa
Storage	27kt
Ships	18kt
Number of ships	1

→ Tank usage Violin Plot



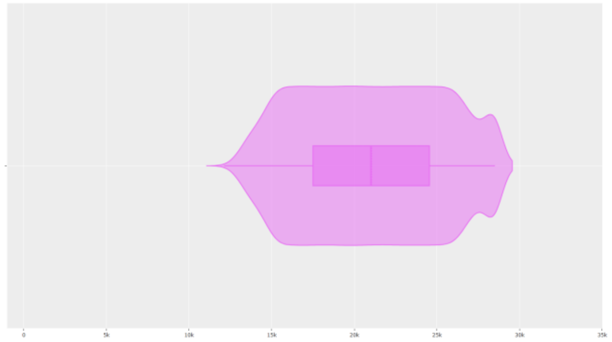
→ Kpis

Parameter	Value
Tank Cost	100,680,000.0€
Fuel Cost	15,432,600.0€
CO2 Storage Cost	180,845,000€
Release CO2 Cost	562,746,575.34€
Total Cost	995,204,175.34€

Bergen 2 ships:

Parameter	Value
Annual production	2400ktpa
Storage	27kt
Ships	18kt
Number of ships	2

→ Tank usage Violin Plot



→ Kpis

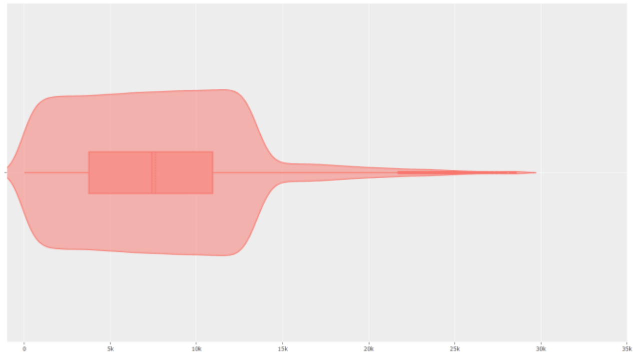
Parameter	Value
Tank Cost	100,680,000.0€
Fuel Cost	30,864,775.0€
CO2 Storage Cost	362,285,000
Release CO2 Cost	43,834,246.58€
Total Cost	808,664,021.58€

PHASE 2 : 2,400 ktpa (Rotterdam/Bergen)

Rotterdam 18k :

Parameter	Value
Annual production	2400ktpa
Storage	27kt
Ships	18kt
Number of ships	1

→ **Tank usage Violin Plot**



→ **Kpis**

Parameter	Value
Tank Cost	100,680,000.0€
Fuel Cost	11,762,300.0€
CO2 Storage Cost	378,665,000.0€
Release CO2 Cost	1,302,739.73€
Total Cost	627,910,039.73€

PHASE 2 : 2.400 ktpa (ROTTERDAM / BERGEN)

Analysis:

- Bergen:
  - With only 1 boat, the cost of the co2 releases justifies investing in a second boat
  - With 2 boats we can see the cost of co2 releases going down, but we can see from the graph that there is not much margin, any important adverse event delaying a boat would increase the penalty cost

- Rotterdam :
  - While the tank has the time to fill up, there is a lot of margin left before it being full.
  - 1 boat with this tank capacity is enough

TNP

HARNESS THE UNPREDICTABLE

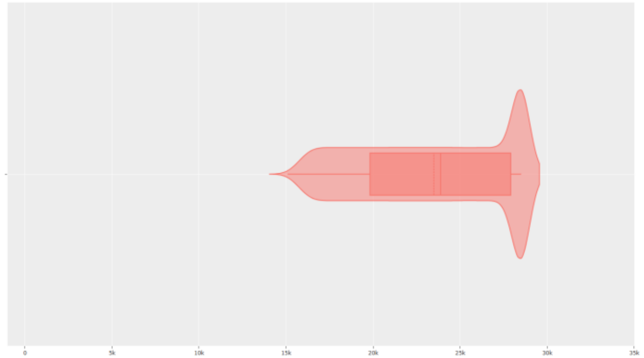
Phase 3 : 3.000 ktpa

PHASE 3 : 3,000 ktpa (Bergen)

Bergen 2 ships :

Parameter	Value
Annual production	3000ktpa
Storage	27kt
Ships	18kt
Number of ships	2

→ **Tank usage Violin Plot**



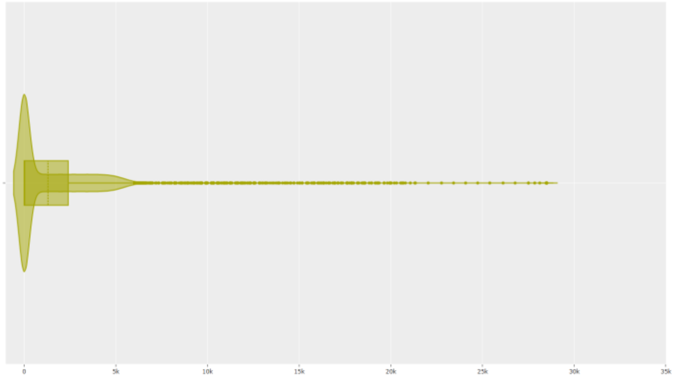
→ **Kpis**

Parameter	Value
Tank Cost	100,680,000.0€
Fuel Cost	30,864,775.0€
CO2 Storage Cost	362,285,000€
Release CO2 Cost	313,454,794.52€
Total Cost	1,078,284,569.52€

Bergen 3 ships:

Parameter	Value
Annual production	3000ktpa
Storage	27kt
Ships	18kt
Number of ships	3

→ **Tank usage Violin Plot**



→ **Kpis**

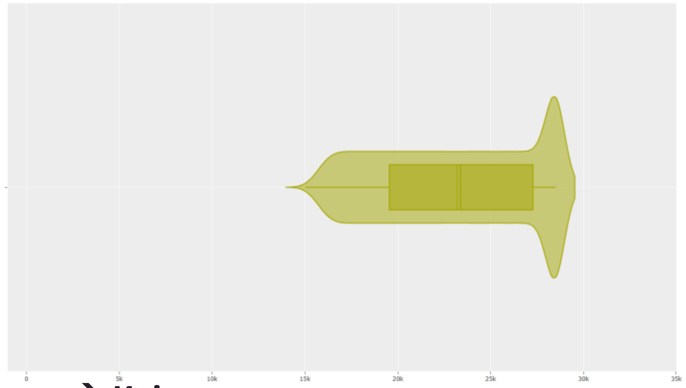
Parameter	Value
Tank Cost	100,680,000.0€
Fuel Cost	40,215,625.0€
CO2 Storage Cost	471,905,000.0€
Release CO2 Cost	1,173,972.6€
Total Cost	1,020,474,597.6€

PHASE 3 : 3,000 ktpa (Rotterdam)

Rotterdam 18k 1 ship :

Parameter	Value
Annual production	3000ktpa
Storage	27kt
Ships	18kt
Number of ships	1

→ Tank usage Violin Plot



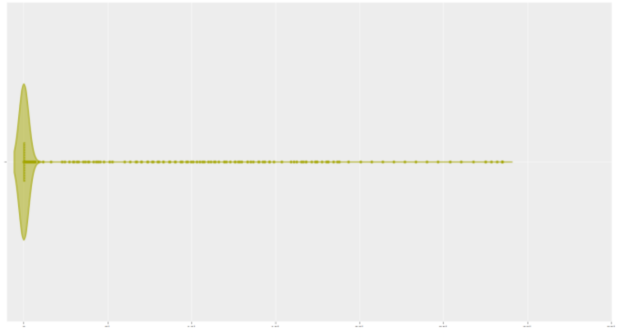
→ Kpis

Parameter	Value
Tank Cost	100,680,000.0€
Fuel Cost	11,895,325.0€
CO2 Storage Cost	382,445,000€
Release CO2 Cost	255,978,082.19€
Total Cost	886,498,407.19€

Rotterdam 18k 2 ships :

Parameter	Value
Annual production	3000ktpa
Storage	27kt
Ships	18kt
Number of ships	2

→ Tank usage Violin Plot



→ Kpis

Parameter	Value
Tank Cost	100,680,000.0€
Fuel Cost	16,254,125.0€
CO2 Storage Cost	471,905,000.0€
Release CO2 Cost	769,863.01€
Total Cost	860,608,988.01€

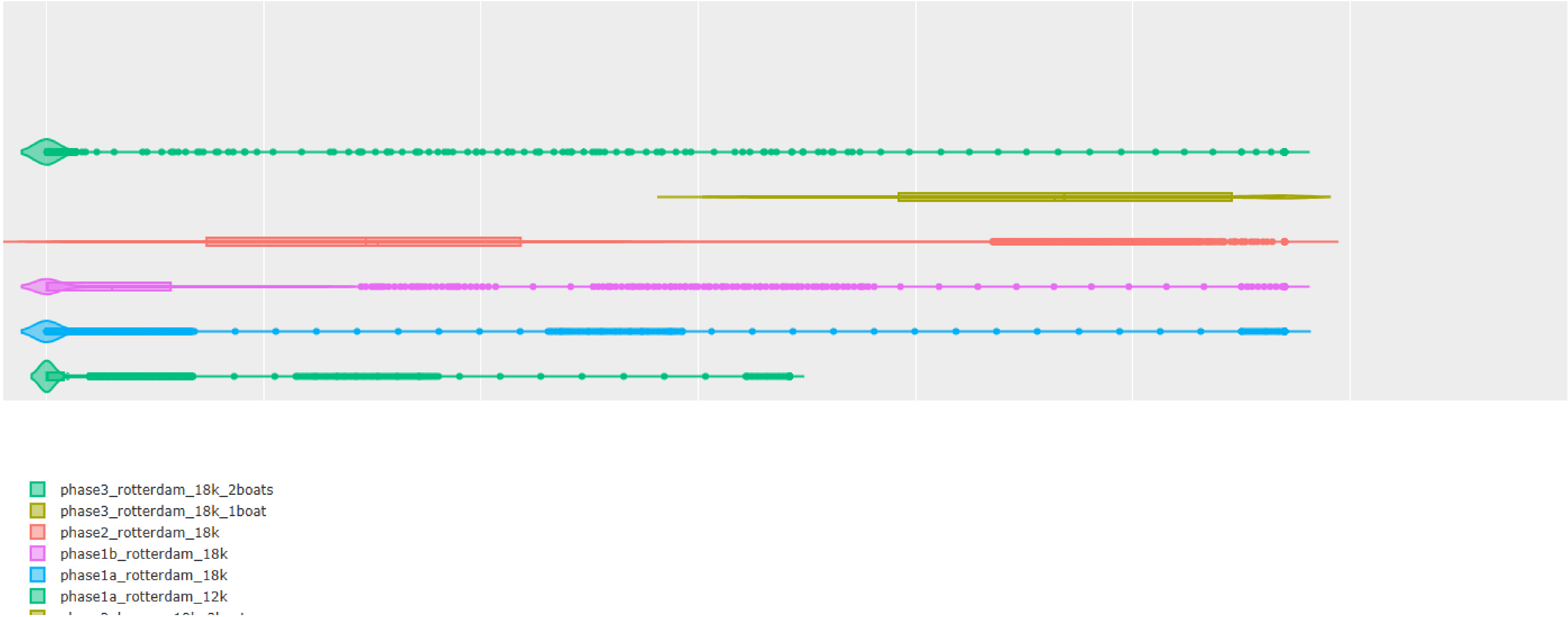
PHASE 3 : 3.000 ktpa (ROTTERDAM / BERGEN)

Analysis:

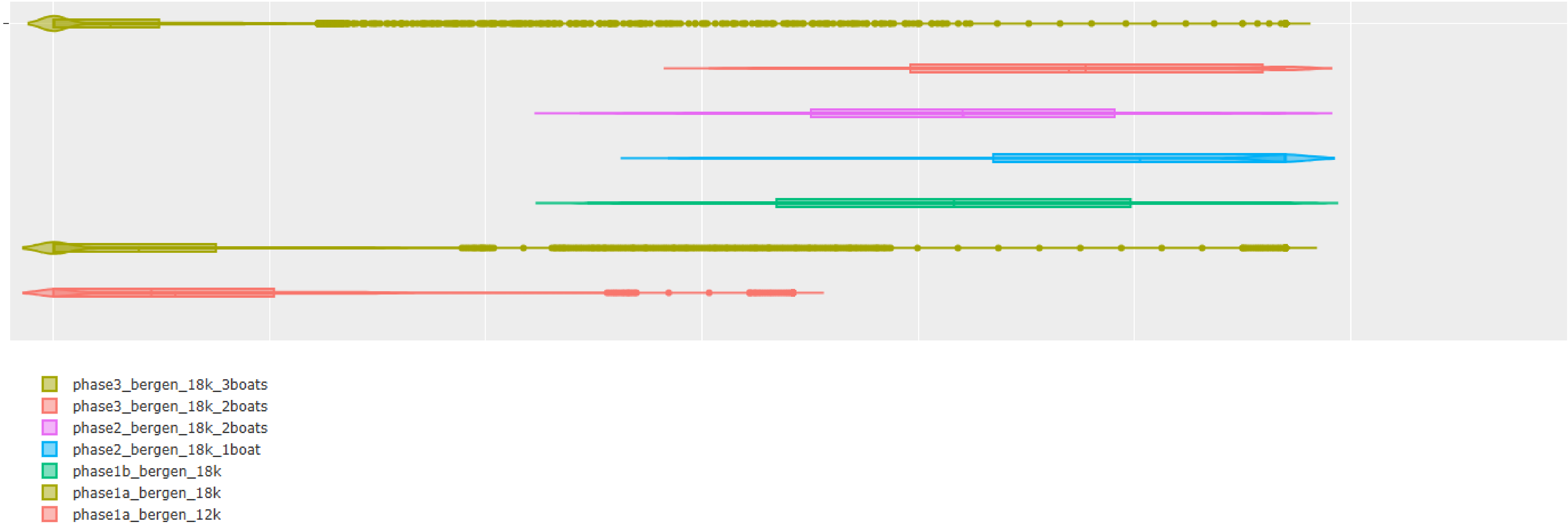
- Bergen
  - 2 boats are not enough to keep up with the production
  - The penalty for releasing the CO_2 justifies investing in an extra boat
  - 3 boats give more than enough transport capacity to follow up with the production
- Rotterdam
  - 1 boat is not enough to keep up with the production
  - The penalty for releasing the CO_2 justifies investing in an extra boat
  - 2 boats give more than enough transport capacity to follow up with the production

- In both case the investment in an extra boat is somewhat downvalued by the increase in costs in storage, fuel, and boats
- The simulation also highlights the extra cost of using Bergen as a storage destination (mostly due to the extra boat needed to avoid paying the CO_2 release fee

Overview Rotterdam



Overview Bergen



Overview

Scenario	Number of Boats	Boat Purchase Cost	CO2 Released Cost	Total Cost
phase1a_bergen_12k	1	135,500,000.0€	682,123.29€	304,909,973.29€
phase1a_bergen_18k	1	135,500,000.0€	686,027.4€	334,702,227.4€
phase1a_rotterdam_12k	1	100,000,000.0€	221,438.36€	261,668,613.36€
phase1a_rotterdam_18k	1	135,500,000.0€	225,342.47€	329,345,542.47€
phase1b_bergen_18k	1	135,500,000.0€	22,998,630.14€	455,456,230.14€
phase1b_rotterdam_18k	1	135,500,000.0€	609,589.04€	432,358,689.04€
phase2_bergen_18k_1boat	1	135,500,000.0€	561,491,780.82€	993,949,380.82€
phase2_bergen_18k_2boats	2	271,000,000.0€	43,363,013.7€	808,192,788.7€
phase2_rotterdam_18k	1	135,500,000.0€	1,302,739.73€	627,270,689.73€
phase3_bergen_18k_2boats	2	271,000,000.0€	314,098,630.14€	1,078,928,405.14€
phase3_bergen_18k_3boats	3	406,500,000.0€	1,194,520.55€	1,021,149,795.55€
phase3_rotterdam_18k_1boat	1	135,500,000.0€	257,005,479.45€	887,525,804.45€
phase3_rotterdam_18k_2boats	2	271,000,000.0€	817,808.22€	860,655,658.22€

CONCLUSION

- Rotterdam
  - Through the simulation we can see that through phase 1a to 2, 1 ship is enough to transport the liquified CO_2 from the production site to the storage site without overflowing the tanks
  - In phase 3 a second ship would be needed to avoid paying a signifant fee for the amount of CO_2 released

- Bergen
  - For phase 1, 1 ship is enough to handle the production load
  - A second ship would be need for phase 2
  - And a third one for phase 3

- In terms of costs, Bergen is consistently more expensive, especially during phase 2 where the price is almost doubled (Either a lot of CO_2 is expelled in the atmosphere, or there is the need to invest in an extra ship)
- On the other hand, Rotterdam increases in cost gradually as the production increases
- Now we would need to test the results of the simulations playing with other parameters combination to try to test the system more.

FUTURE DEVELOPMENT / IMPROVEMENT OF THE MODEL TO MADE BY AIR LIQUID TEAM OR FUTURE TNP COLLABORATION

Future Improvements :

- Take into account extra costs:
    - Boat maintenance
    - Delay penalties
    - Crew and crew management costs
    - ...

- Add an interface to be able to manipulate the variables of the simulation before running it
- Add an interface to open a scenario file and be able to edit it directly from the interface
    - Via streamlit/.exe
    - Via an excel macro
- Add an interface to list all scenarios in a folder/subfolders and select the ones to run
- Display the result in the same interface used to run the one or multiple scenarios
- The development time and cost of those improvements need to be estimated

CO2 SOURCE SIMULATION

Remarks :

- To better consider the production context of the Liquefaction factory, we modeled 5 independent sources with their own independent probability of failure.
- When a failure happens in one of the source, the production for that source stops completely, without impacting the rest of the sources.
- This results in a reduced production rate from the Liquefaction factory