Feasibility and Performance Evaluation of Cargo Drones for Offshore Wind farm Operations

PRIMA-Cargo Drone

GROW Common / PPS Fund Project

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Summary

The feasibility and performance of cargo drones (CD) for the delivery of spare parts and tools in offshore wind farm (OWF) operations have been assessed in this project through both field trials as well as simulation-based business case evaluations.

Field Trials

Four offshore field trials were conducted at Vattenfall's DanTysk/Sandbank wind farm during November- December 2024. Cargoes weighing up to 30kg were delivered by a CD from an SOV to the wind turbine (short-range deliveries <5km) within a duration of 8 minutes, demonstrating the efficiency of CD transfer compared to CTV transfer which takes up to 1 hour. Moreover, CDs successfully operated in moderate weather conditions (U_w<5m/s; H_s<1.5m), where HSE and risk mitigation strategies were properly implemented (i.e. bird strikes and impacts of drones on birds were monitored). Operational recommendations are shared in the field-trial report.

Business Case Evaluation

TNO's logistical simulation tool, UWiSE, was used to quantify the add-values of using CD in OWF operations. A case study at IJmuiden Ver (15MW × 134 turbines) adopting SOV-based strategy was modelled, exploring the CD use cases of (i) express unmanned ad-hoc delivery of missed tools/parts and (ii) pre/un-loading of cargos to/from nacelle. It is found that the overall cost, including vessel fuel cost and downtime revenue loss, is reduced by 436 k€/y (-18% from No CD case) for minor corrective maintenance and 241 k€/y (-7% from No CD case) for scheduled maintenance. Nevertheless, limitations of the assessment are acknowledged, with the key uncertainty being the frequency of missing cargo events, which is a critical factor determining the results and requires verification from industry.

List of Content

Chapter 1 - Project Introduction

PRIMA - CD

Pathways towards Remote Inspection & Maintenance of offshore wind Assets, using Cargo Drones

Goals:

1. On-site testing to evaluate the operations, challenges, and lessons learned to refine cargo drone's deployment in offshore environments.
2. Perform high-fidelity simulation to quantify the cost effectiveness and emission reduction of using cargo drone in long term operations & maintenance, with impacts on:

- Vessel fuel cost
- Vessel CO_2 Emissions
- Downtime of assets

Field Test - Ampelmann

Onshore test:

- Set-up time
- Transfer times per distance travelled.
- Determine maximum range per payload (5kg – 40 kg, in steps of 5kg).

Offshore test:

- Part one: Multiple runs on WTG (cargo dropping)
  - Measure electromagnetic interference (EMI) around WTG that may hamper operations/ flight time
  - Validate workability parameters
  - Simulation runs: set-up time, take-off and transit time, approach WTG and return to vessel, landing procedure.
    - *During Dynamic Position of vessel*
    - *During sail (take off/landing on different coordinates)*
- Part two: Trial and data collection; use case validation for express delivery and scheduled maintenance

Work Plan

Work Package	Expected tasks	Timeline
WP1: Scenario Definition	• Workshop to establish scenarios • Input gathering • Setting the KPIs	May 2024 – July 2024
WP2: Field test	• Onshore test • Offshore test	May 2024 – Sep 2024
WP3: Analysis	• Baseline scenario simulation • Sensitivity analysis	Aug 2024 – Dec 2024
WP4: Dissemination	• Workshop to discuss results • Presentation in the GROW meeting –Mar 2025	Jan 2025 – Mar 2025

Chapter 2 - Dantysk/Sandbank Cargo Drone Trial

Highlights from Offshore Trial at Dan tysk wind farm

Trials planned from Nov 27 – Dec 07, 2024. 2 operational days achieved - Four flights were conducted during the trial, including one test flight and three operational flights. Flight details as follows:

- flights between the SOV Acta Centaurus and various wind turbines within the offshore wind farm
- M300 test flight lasting 8.5 minutes with nacelle inspection simulation
- FC30 test flight lasting 5 minutes with no payload and covering 1.839 meters,
- a cargo delivery to WT -SB65 lasting 8 minutes with a 30 kg payload, and
- an additional cargo flight lasting 9 minutes with a 20 kg payload
- UAV operations were executed in moderate weather conditions, with winds at 5 m/s and a sea state of Hs = 1.5m.

Challenges:

Weather was a big challenge since the trials were conducted in November- December. A sea state of HS2.5-3.0 made UAV landing challenging on the vessel’s aft deck.

Highlights from Offshore Trial at Dan tysk wind farm

Key Findings:

- UAVs are efficient esp for short range transfers and deliveries (< 5km) – delivery time in less than 9 minutes compared to CTV transfers up to 1 hour.
- Proper HSE sessions and risk mitigation strategies with all involved parties helped in identifying and eliminating potential risk – bird strikes on the drone and the impact of drones on the birds were monitored.
- UAVs were able to fulfil the flight requirements and deliveries in moderate sea states and high wind speeds.
- For take-off and landing, positioning the vessel bow into the wind helped in reducing deck motion and improving UAV handling and workability, therefore making this as an operational recommendation.
- Communication with the Maritime Control Center (MCC) was efficient, enabling rapid approvals

Highlights from Offshore Trial at Dan tysk wind farm

Major Lessons learnt:

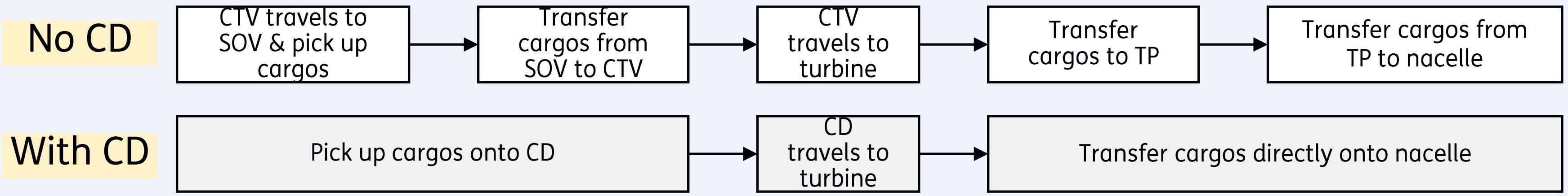
- Limited deck space availability on the vessel , which highlighted the need for future projects to consider flying from 20-foot containers to optimize space usage.
- BSH permits to be checked and revised if needed in advance, to avoid any delays.
- Proper integration of UAV operations in to vessel workflows required.

Chapter 3 - Logistics Modelling of Cargo Drone Use Cases

Cargo Drone (CD) Use Cases

In offshore wind farms during O&M phase, the following cargo drones (CD) use cases are explored:

Use Case 1: Express unmanned ad-hoc delivery of missed tools/parts [1]



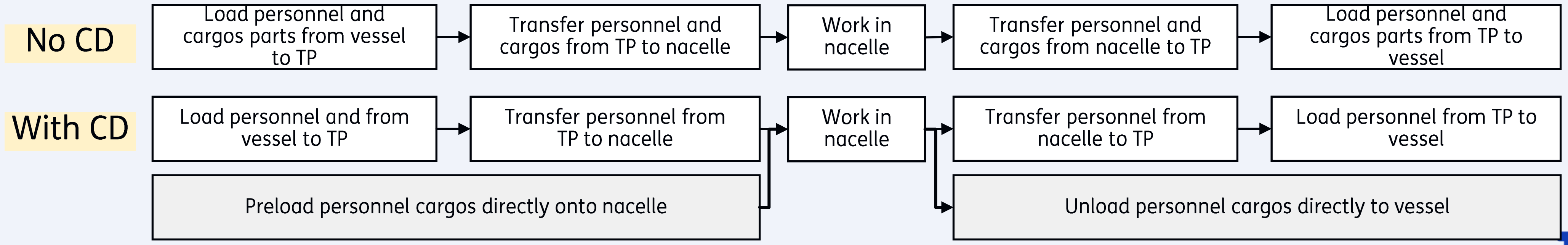
Benefit of CD

- Saving ~1.1h per delivery
- Carbon free (no vessel)

Use Case 2: Pre/un-loading of cargos to/from nacelle [1]

Preloading saving ~0.5h

Unloading saving ~0.5h



[1] Detailed breakdown of time estimation is given in Appendix A

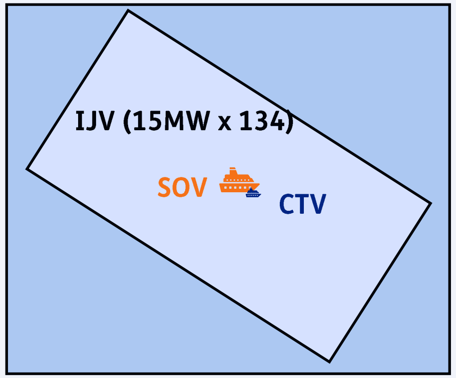
Simulation Scope

The offshore wind farm site Ijmuiden Ver with capacity of 2GW (15MW x 134) is modelled.
For each scope, both CD use cases of (1) ad-hoc delivery + (2) pre/un-loading are included.

Scope 1: Minor Corrective & Trouble Shooting

Assuming a SOV is chartered and stationed at the center of the wind farm and a CTV is deployed to turbines during the day shift, with 4 separate teams (each consisting of 3 technicians) available. The fuel consumption of CTVs used for dispatching and ad-hoc deliveries is considered in the analysis.

Event Fequency	Work on Turbine
1/turbine/y	h/event
7 [1]	4



To qunantify the uncertainty of missing tools/ parts occurrence, two scenarios are modelled:

In **Baseline** scenario, the frequency of missing cargos is 1/turbine/y (meaning once every 7 events)

In **Sensitivity** scenario, the frequency of missing cargos is 2/turbine/y (meaning twice every 7 events)

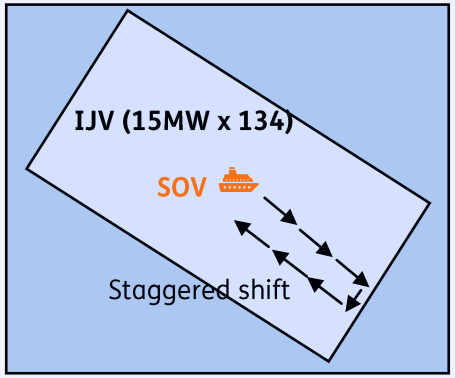
Simulation Scope

The offshore wind farm site Ijmuiden Ver with capacity of 2GW (15MW x 134) is modelled.
For each scope, both CD use cases of (1) ad-hoc delivery + (2) pre/un-loading are included.

Scope 2: Scheduled Maintenance

Assuming a SOV is chartered at site during summer period (Apr-Sep) each year for scheduled maintenance. SOV is deployed to turbines during the day shift, with 3 separate teams (each consisting of 5 technicians) available. The fuel consumption of a SOV due to scheduled maintenance activities during the daytime and a CTV used for ad-hoc deliveries are considered in the analysis.

Event Fequency	Work on Turbine
1/turbine/y	h/event
1[1]	30 (splitted to 3 days)

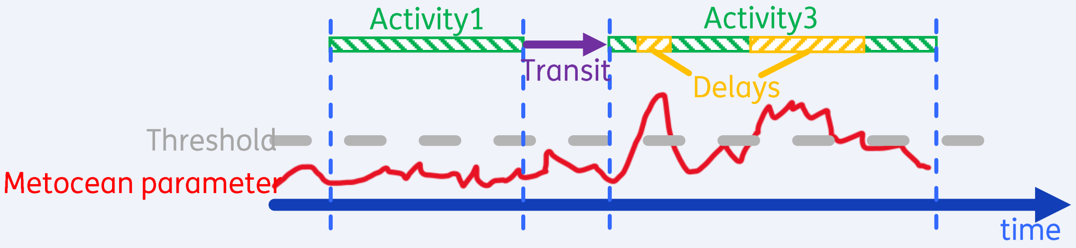


- It is assumed that for each turbine scheduled maintenance, 1 out of 3 days would encounter missing tools or spare parts.
- Tools and spare parts are loaded on the 1st day and remain on the turbine until the tasks are completed on the 3rd day.

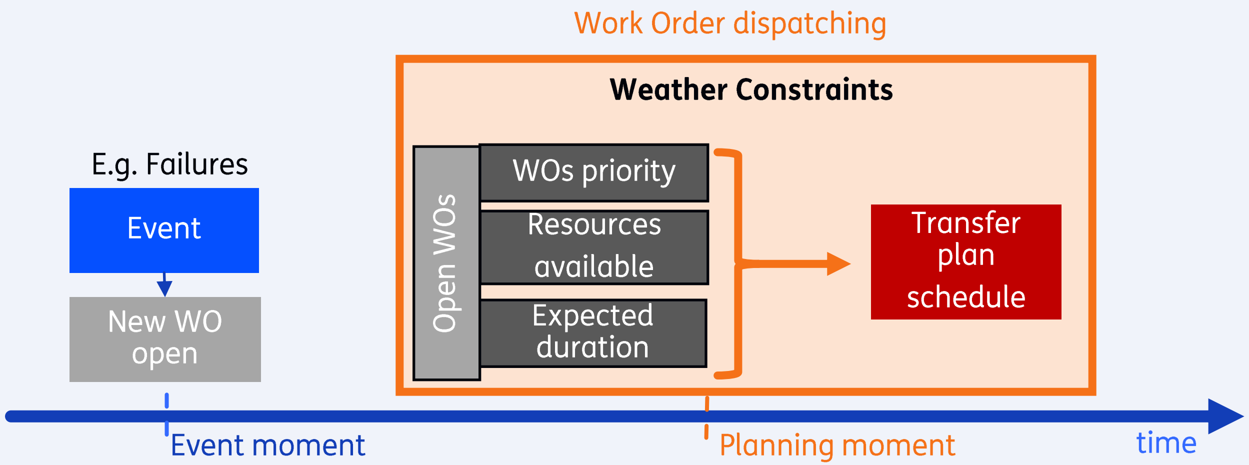
Methodology

TNO UWiSE is used to perform the logistical modelling of offshore wind farm, considering the weather dependencies and daily planning algorithms.

Marine Operations on Weather Dependencies



Daily Planning Algorithms



The following **KPIs** over 20 years of lifetime are evaluated to quantify the potential benefits of adopting CD compared with the ones without CD:

1. Vessel fuel cost (k€/y)
2. Vessel CO_2 emission (ton/y)
3. Wind farm downtime revenue losses (k€/y)

Remark: Costs for vessel chartering, human resources and cargo drones related to minor corrective maintenance, trouble-shooting visits, and scheduled maintenance are treated as fixed project costs and are therefore not included as KPIs for comparison.

Simulation Assumptions (project-specific)

Vessel Inputs

- CTV's operating and idling fuel consumption rate is 500 l/h and 50 l/h, respectively
- CTV's average speed of 20 knot
- CD's average speed of 40 knot
- CTV's operating constraint: $H_s \leq 1.5m$, $U_w \leq 15m/s$
- SOV's operating and DP fuel consumption rate is 500 l/h
- SOV's operation constraint: $H_s \leq 3.0m$, $U_w \leq 17m/s$
- Fuel cost rate is 1.2 €/l [1]
- CO_2 emission factor is 3 kg/l [2]

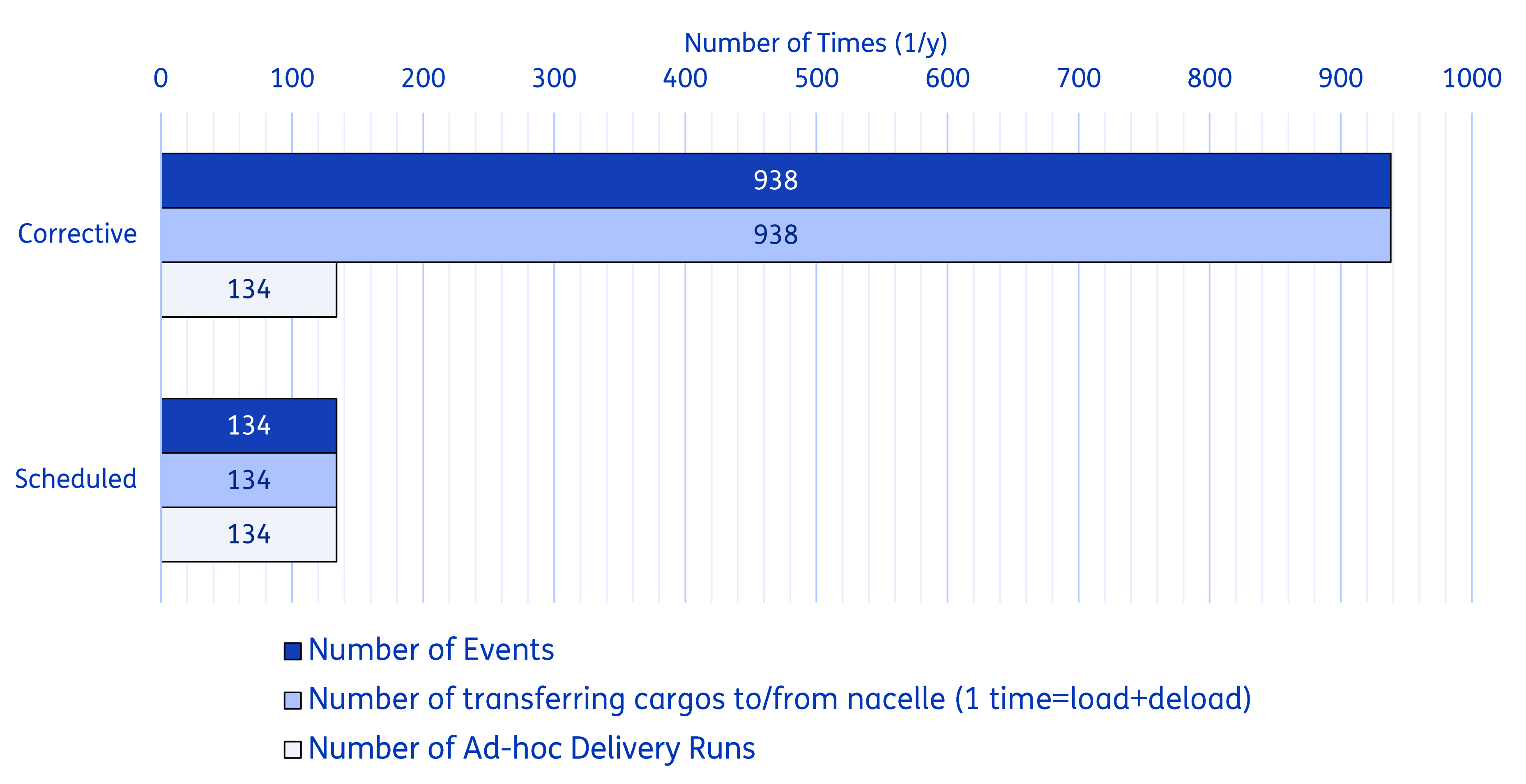
Assumptions

- The wholesale electricity prices [3] in the Netherlands is 80 €/MWh in the scope of simulation.
- Wind turbine would be temporarily turned on during off-shift nighttime if the work is split across multiple days.
- On the day when CTV/SOV sails out, the weather condition is assumed to be suitable for cargo drone's operation.

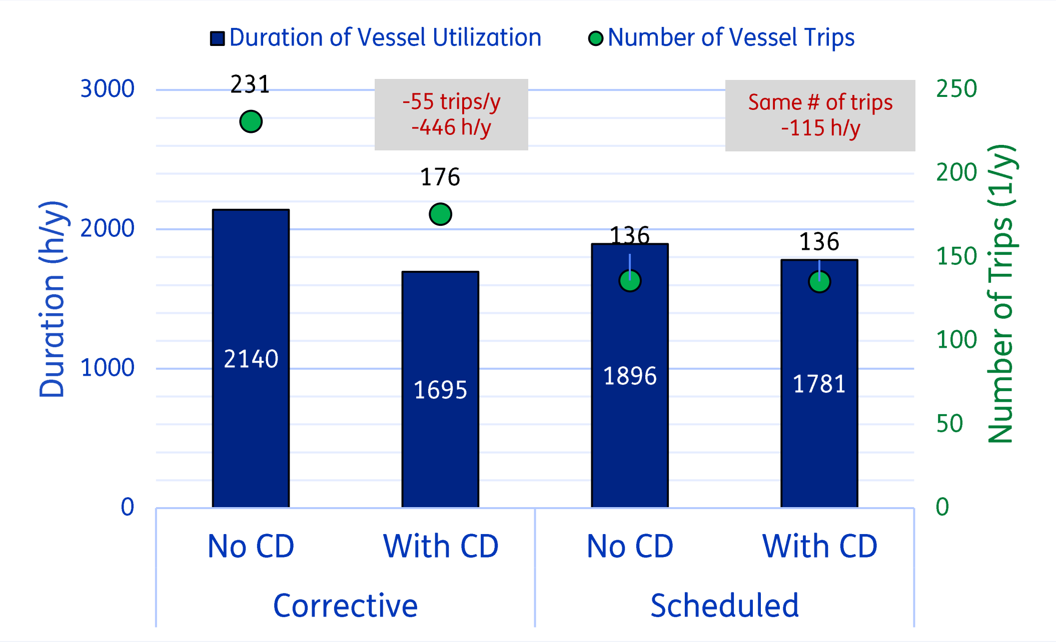
[1] Statista. (n.d.). Average monthly prices of marine and agricultural diesel in Spain from January 2020 to February 2024 (in euros per liter). Statista. Retrieved February 14, 2025, from: website
[2] Climatiq. (n.d.). Marine diesel oil (MDO) – well-to-tank emissions factor. Climatiq. Retrieved February 14, 2025, from: website
[3] S&P Global. (2024, June 12). *Netherlands awards 4 GW offshore wind in biggest tender amid complicated market conditions.* S&P Global Commodity Insights. Retrieved from: website

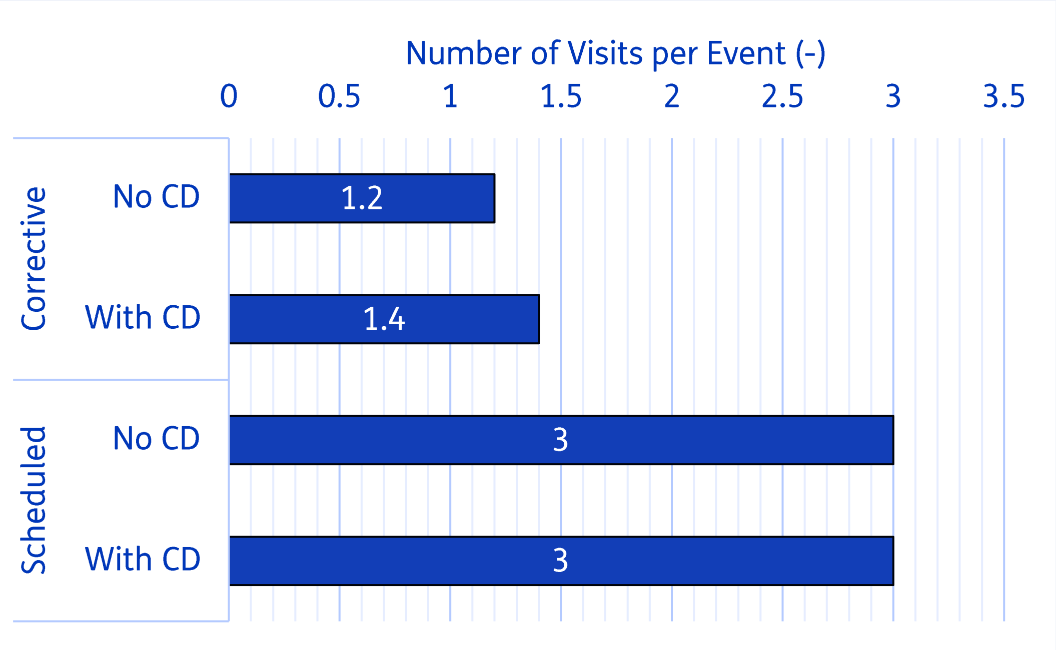
Results

Annual Events



Vessel Utilization





Corrective maintenance:

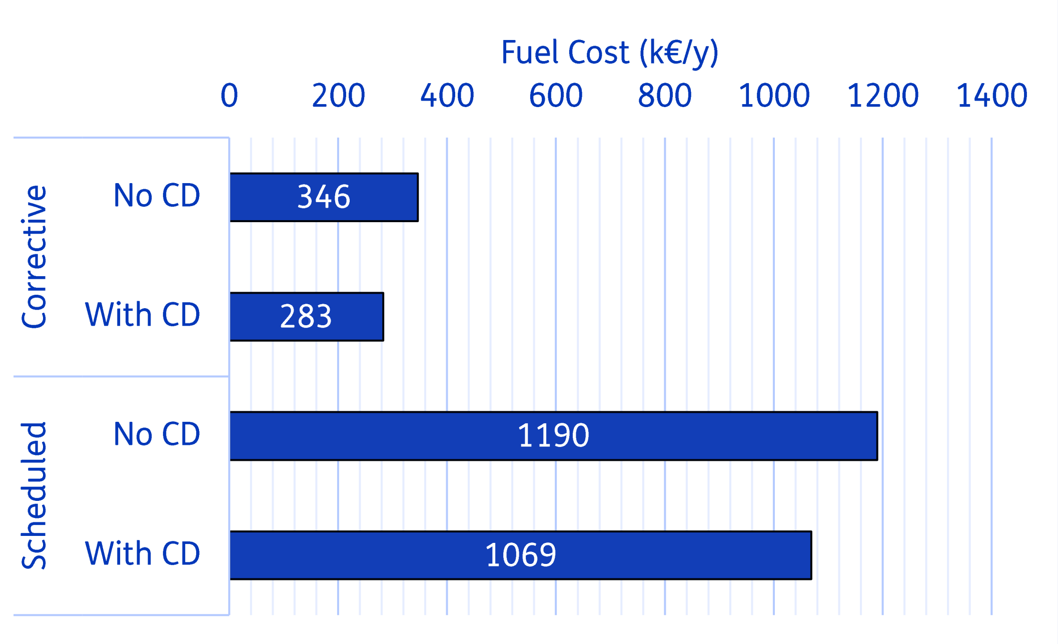
- The number of vessel trips is reduced by **55 trips/y**, as more tasks are likely to be planned in the same trip due to reduced work time per task.
- On the other hand, the task is also more likely to be distributed across more than 1 day, resulting in a slightly increased number of visits per event (as shown in the right figure). This may cause extra downtime due to more technician transferring activities.
- Overall, CTV utilization duration is reduced by **446 h/y** due to less work hours saved by CD usage and less number of vessel trips.

Scheduled maintenance:

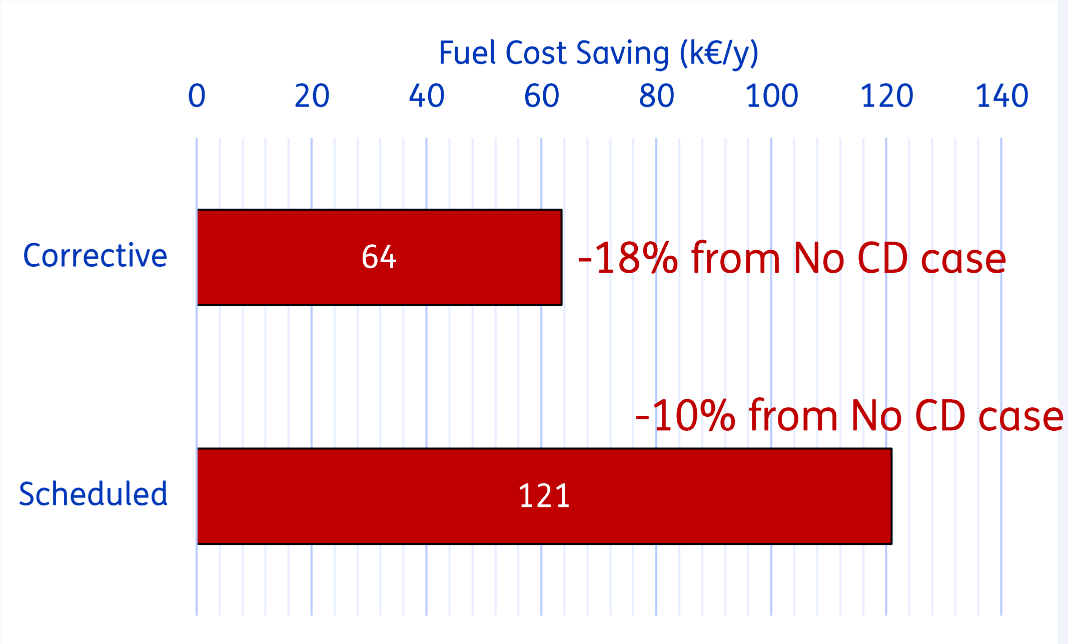
- The number of SOV trips remains the same, since the planning of scheduled maintenance is more fixed, where 3 turbines are planned to be visited each day.
- Overall, SOV utilization duration is reduced by **115 h/y** due to less work hours saved by CD usage

Fuel Cost

Absolute Value



Difference between CD case and No CD case



Remark: For scheduled maintenance, the fuel cost accounts only for daytime operations related to scheduled maintenance activities. The waiting period at night is excluded from the analysis, as minimal differences are expected between the two scenarios.

Corrective maintenance:

- Fuel cost saving of CTV is **64 k€/y** (-18% from NO CD case)
- The extent of fuel cost saving for corrective maintenance is more significant than for scheduled maintenance, primarily due to the reduction in vessel trips (see vessel utilization).

Scheduled maintenance:

- Fuel cost saving of SOV and CTV (for ad-hoc delivery) is **121 k€/y** (-10% from NO CD case)

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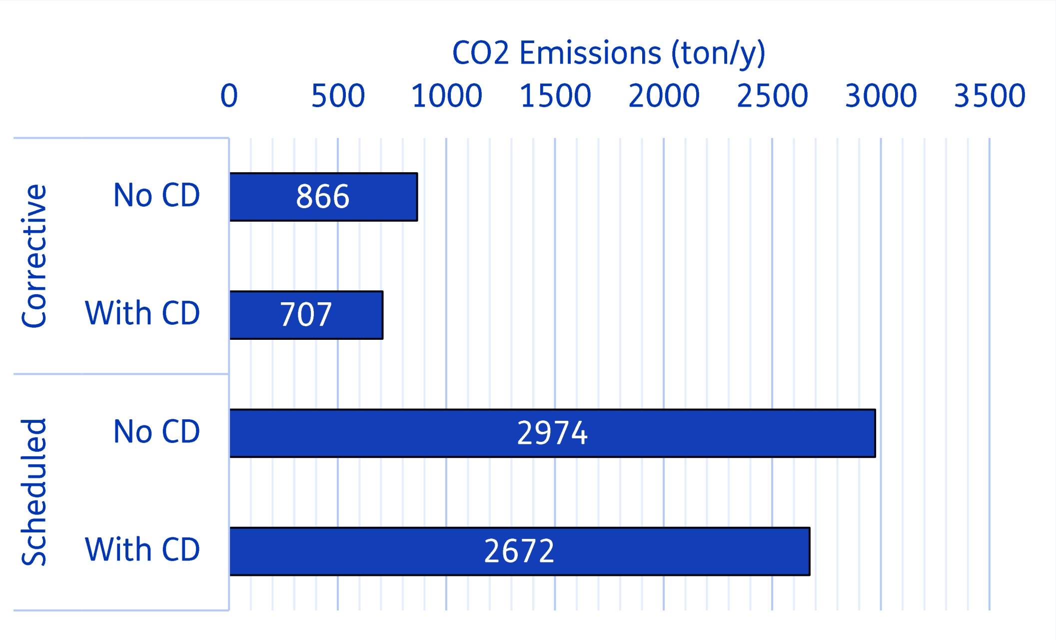
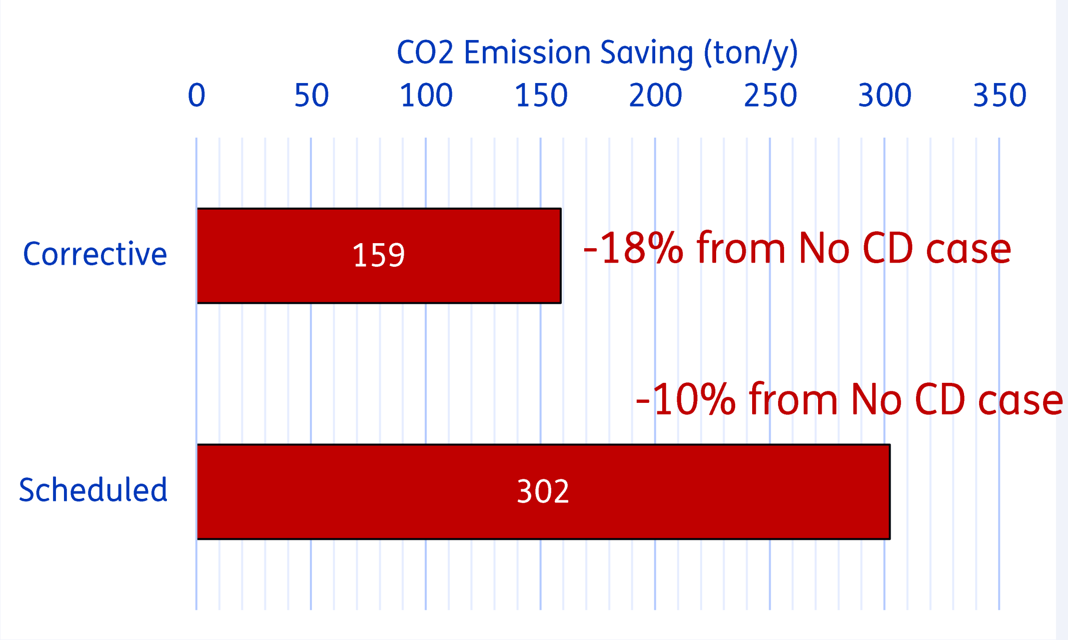
CO_2 Emissions

Absolute Value



Difference between CD case and No CD case



Remark: For scheduled maintenance, the CO_2 emission accounts only for daytime operations related to scheduled maintenance activities. The waiting period at night is excluded from the analysis, as minimal differences are expected between the two scenarios.

Corrective maintenance:

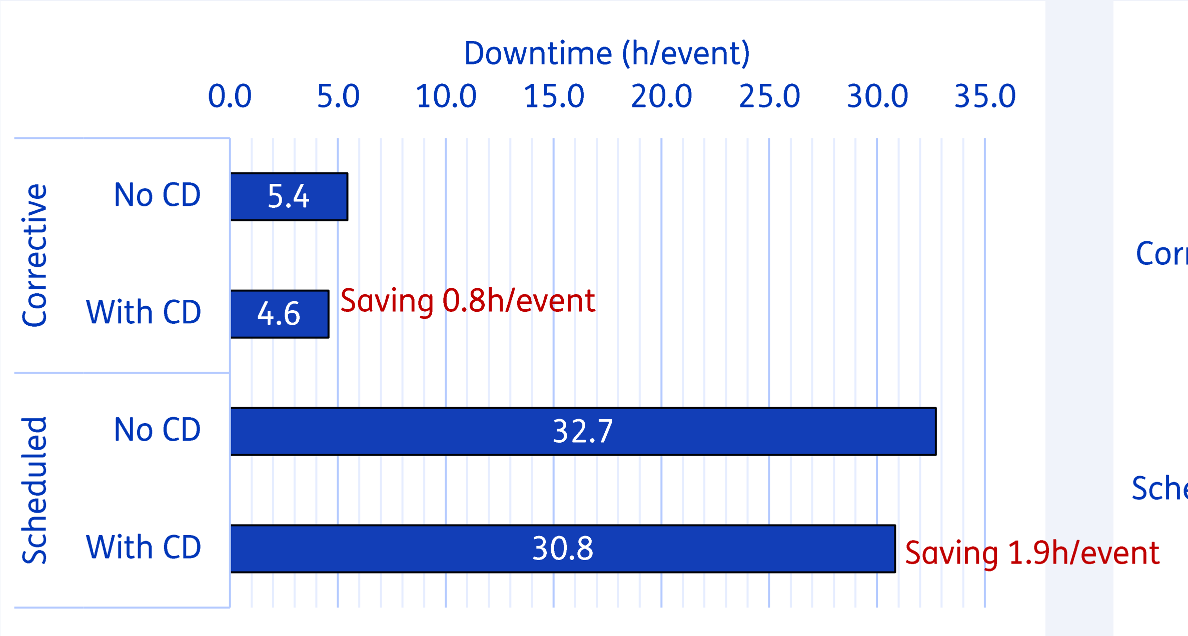
- CO_2 emission saving of CTV is **159 ton/y** (-18% from NO CD case)
- The extent of fuel cost saving for corrective maintenance is more significant than for scheduled maintenance, primarily due to the reduction in vessel trips (see vessel utilization).

Scheduled maintenance:

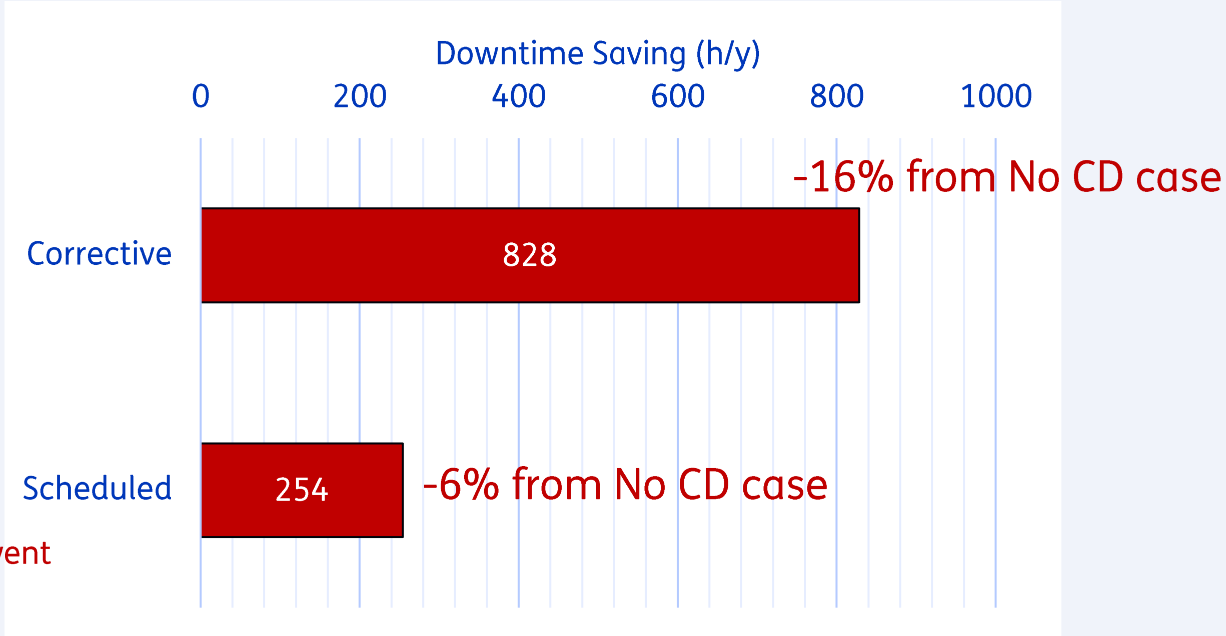
- CO_2 emission saving of SOV and CTV (for ad-hoc delivery is **302 ton/y** (-10% from NO CD case)

Downtime

Absolute Value



Difference between CD case and No CD case



Corrective maintenance:

- Downtime saving per event is **0.8 h/event**
- Downtime saving per event includes the direct time reduction achieved through CD usage [1], slightly offset by the higher number of technician transferring activities (see vessel utilization), and some other planning factors (e.g. waiting vessel to pick up technicians).

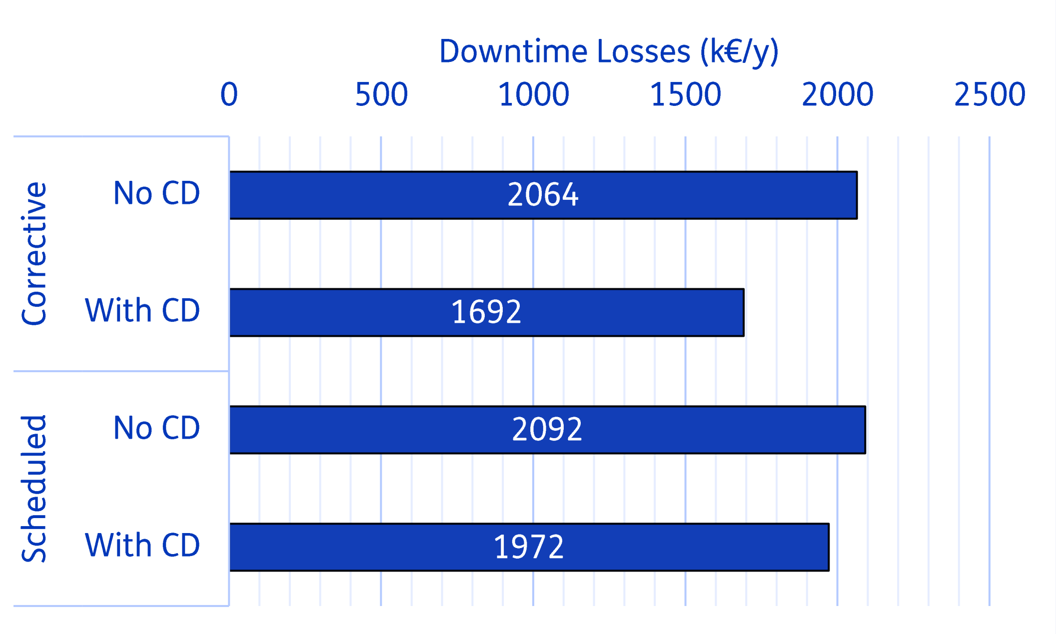
Scheduled maintenance:

- Downtime saving per event is **1.9 h/event**
- Downtime saving per event includes the direct time reduction achieved through CD usage [2], sightly offset by some other planning factors (e.g. waiting vessel to pick up technicians).

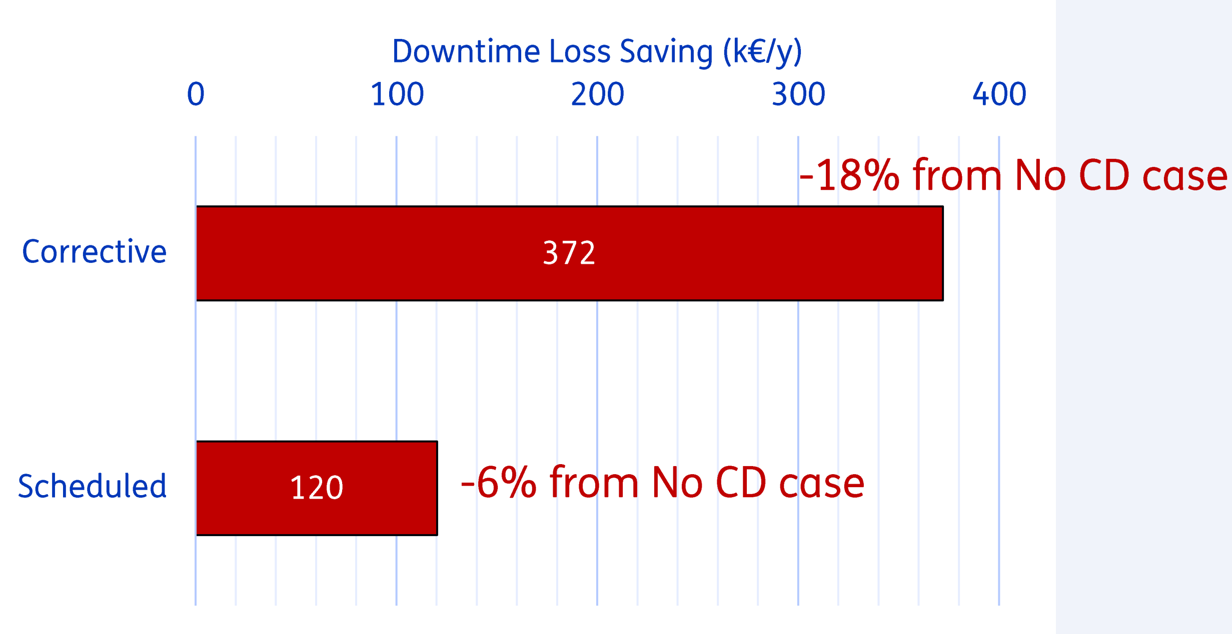
[1] For corrective maintenance, there is approximately 1.2h direct time saving per event by CD usage. Out of this 1.2h (~80%), 1h is contributed by pre/deloading use case and 0.2h (~20%) by ad-hoc delivery use case.
[2] For scheduled maintenance, there is approximately 2.1h direct time saving per event by CD usage. Out of this 1h (~50%), 1h is contributed by pre/deloading use case and 1.1h (~50%) by ad-hoc delivery use case.

Downtime Revenue Loss

Absolute Value



Difference between CD case and No CD case

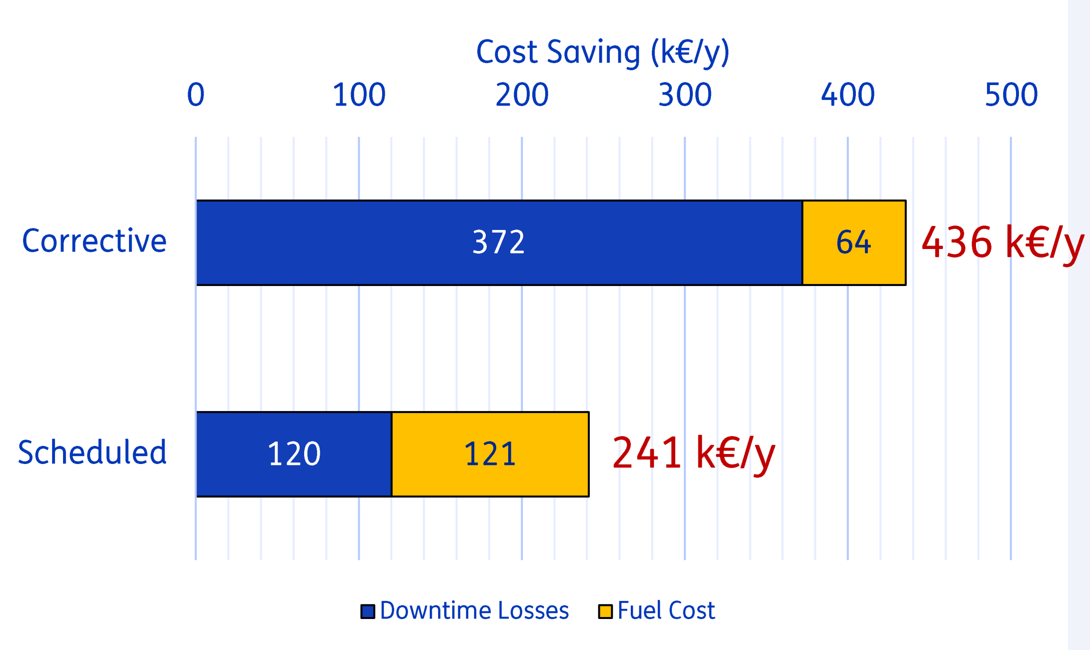


Corrective maintenance:
- Downtime revenue loss saving is **372 k€/y** (-18% from NO CD case)

Scheduled maintenance:
- Downtime revenue loss saving is **120 k€/y** (-6% from NO CD case)

Overall Cost Saving

Difference between CD case and No CD case



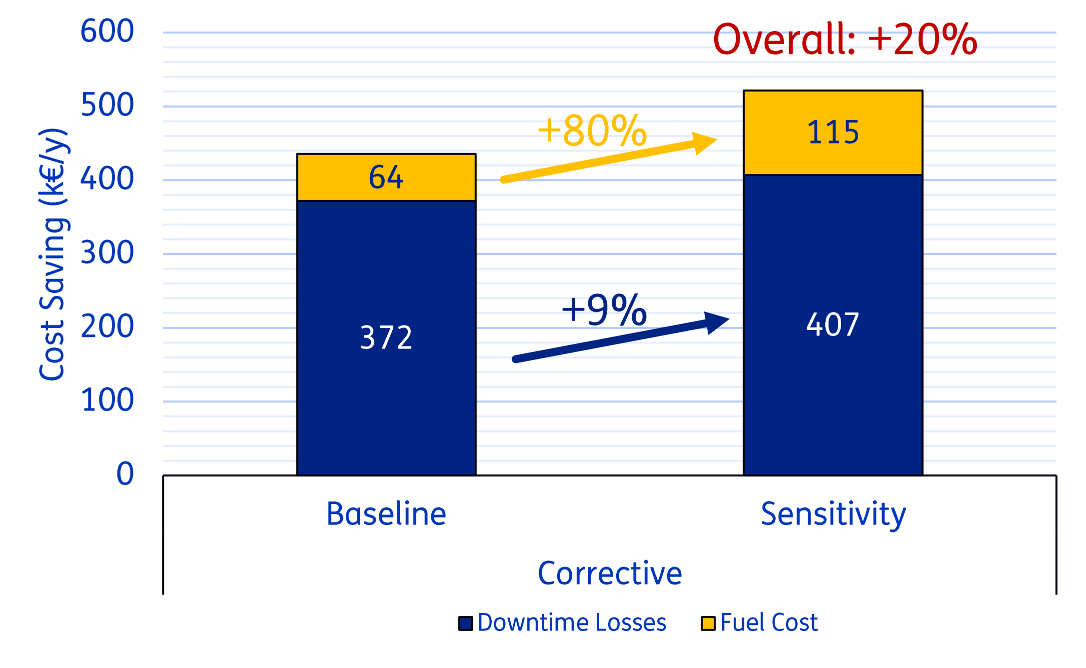
Corrective maintenance:
- Overall cost saving (fuel cost + downtime revenue loss) is **436 k€/y** (-18% from No CD case)

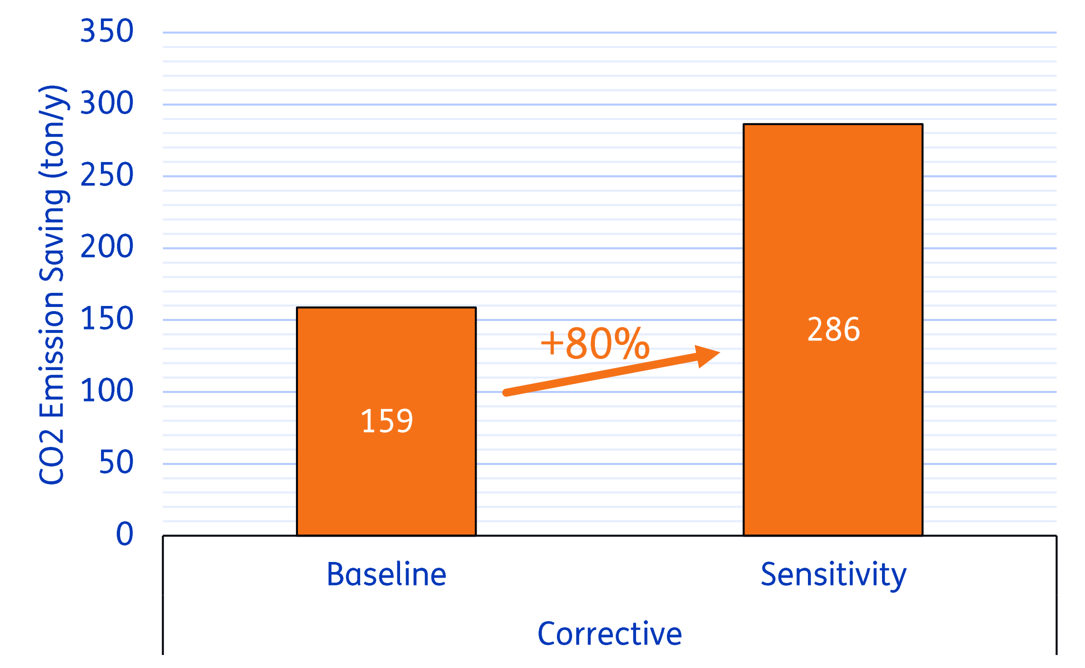
Scheduled maintenance:
- Overall cost saving (fuel cost + downtime revenue loss) is **241 k€/y** (-7% from No CD case)

Sensitivity Analysis (Corrective Maintenance)

In **Baseline** scenario, the frequency of missing cargos is **1/turbine/y** (meaning once every 7 events)

In **Sensitivity** scenario, the frequency of missing cargos is **2/turbine/y** (meaning twice every 7 events)





It is shown that for corrective maintenance, the frequency of cargo missing has sensitive impact on fuel consumption saving. For the downtime saving, it is less affected, since most of the downtime saving is contributed by CD usage in pre and deloaing of cargos (see remarks in Slide).

Chapter 4 - Conclusions

Conclusions

Summary of Scope

This study explores the potential use cases of cargo drones (CDs) in offshore wind farm O&M, specifically:

(i) Express unmanned ad-hoc delivery of missed tools/parts
(ii) Pre/un-loading of cargo to/from the nacelle.

The long-term benefits are assessed using the TNO UWiSE logistical model over a 20-year lifespan, incorporating weather dependencies and resource planning. Key performance indicators (KPIs) are evaluated, including:

(i) fuel costs
(ii) CO_2 emissions
(iii) downtime-related revenue losses.

As a case study, an offshore wind farm at IJmuiden Ver (15MW × 134 turbines) is modeled, considering two maintenance scopes with SOV-based strategy, where each scope includes both the use cases mentioned above:

Scope 1 - Minor Corrective & Troubleshooting
Scope 2 - Scheduled Maintenance.

Conclusions

Key Findings:

1. Direct time savings in CD use cases are estimated as below (in IJV site)

(i) Express unmanned ad-hoc delivery of missed tools/parts: saving 1.1h per delivery
(ii) Pre/un-loading of cargo to/from the nacelle: saving 0.5h per loading + 0.5h per unloading

2. More efficient Vessel Utilization

- Corrective Maintenance: With the involvement of cargo drones into logistics, work duration per task has shortened which not only reduces the CTV operational time directly but also facilitates better vessel utilization. The number of CTV trips is reduced by 55 annually. Overall, it saves **446h** of CTV operation each year.
- Scheduled Maintenance : With the involvement of cargo drones into logistics, work duration per task has shortened which reduces the SOV operational time directly. Since the scheduled maintenance is planned upfront, the number of SOV trips remains the same. Overall, it saves **115h** of SOV operation each year.

Conclusions

Key Findings:

3. Less Fuel Consumption

- Corrective Maintenance: Due to reduced CTV operational time, and the avoidance of using CTV to pick up missing cargos, the fuel cost is reduced by **64 k€/y (-18%)** and the CO_2 emission is reduced by **159 ton/y (-18%)**
- Scheduled Maintenance: Due to reduced SOV operational time, and the avoidance of using CTV to pick up missing cargos, the fuel cost is reduced by **121 k€/y (-10%)** and the CO_2 emission is reduced by **302 ton/y (-10%)**

4. Less Downtime Revenue Losses

- Corrective Maintenance: Due to direct time saving by CD usage, while slightly compensated by additional teachnician transferring activities and other planning factors, the downtime revenue losses is reducced by **372 k€/y (-18%)**
- Scheduled Maintenance: Due to direct time saving by CD usage, while slightly compensated by other planning factors, the downtime revenue losses is reduced by **120 k€/y (-8%)**

Conclusions

Key Findings:

5. Impact of higher chances of cargo missing

- In corrective maintenance, the frequency of missing cargo events is uncertain. In the Baseline scenario, it is assumed to occur once every seven corrective events. To assess the impact of this parameter, a Sensitivity scenario is evaluated, assuming missing cargo occurs twice every seven corrective events. The analysis shows that fuel consumption savings are highly sensitive to the frequency of missing cargo events. However, downtime savings are less affected, as the majority of downtime reduction comes from the use of CD during preloading and unloading of cargos.

Limitations of this Study

1. The frequency of cargo missing both for both corrective and scheduled maintenance remains unknown to the industry, representing a major source of uncertainty in this analysis.

2. The simulation does not account for the granularity of event occurrences. In reality, maintenance tasks vary in operational requirements, such as work duration, crew size, and event frequency. Some tasks cannot be split across multiple visits, while others may require several visits, with turbines remaining shut down overnight. These complexities are not considered in this study.

3. The study assumes that all necessary tools can be delivered by cargo drones, which may not be feasible due to weight constraints.

4. The operational costs of cargo drones have not been included in this analysis.

5. The requirements for (de)preloading cargo for scheduled maintenance may differ from those for corrective maintenance, but this distinction has not been addressed in the study.

6. The possibility of 24-hour operations for both corrective and scheduled maintenance has not been explored in this study and remains an area of interest for future research.

Thank you

Appendices

Appendix A

Method Statement: Corretive and Trouble-Shooting

#	Step	No CD	With CD
1	Load personnel, tools & spare parts to CTV	30 min	
2	CTV travels to wind turbine	Distance/ CTV speed	
3	Turn off wind turbine	-	
4	Load personnel, tools & spare parts from CTV to TP	15 min	10 min
5	Transfer personnel, tools & spare parts from TP to nacelle	35 min	10 min
6	Technician crew carry out works (including lunch break)	4 h	
7	Transfer cargos & technician crew back from nacelle to TP	35 min	10 min
8	Load personnel, tools & spare parts from TP to CTV	15 min	10 min
9	Turn on wind turbine	-	
10	CTV travels back	Distance/ CTV speed	
11	Unload personnel, tools & spare parts to CTV	30 min	

Method Statement: Scheduled Maintenance

#	Step	No CD	With CD
1	Breefing, checking of tools and equipment and getting ready	30 min	
3	Turn off wind turbine	-	
4	Load personnel, tools & spare parts from SOV to TP	15 min	10 min
5	Transfer personnel, tools & spare parts from TP to nacelle	35 min	10 min
6	Technician crew carry out works (including lunch break)	10 h (each day) x 3 days	
7	Transfer cargos & technician crew back from nacelle to TP	35 min	10 min
8	Load personnel, tools & spare parts from TP to SOV	15 min	10 min
9	Turn on wind turbine	-	
10	Breefing, checking of tools and equipment	30 min	

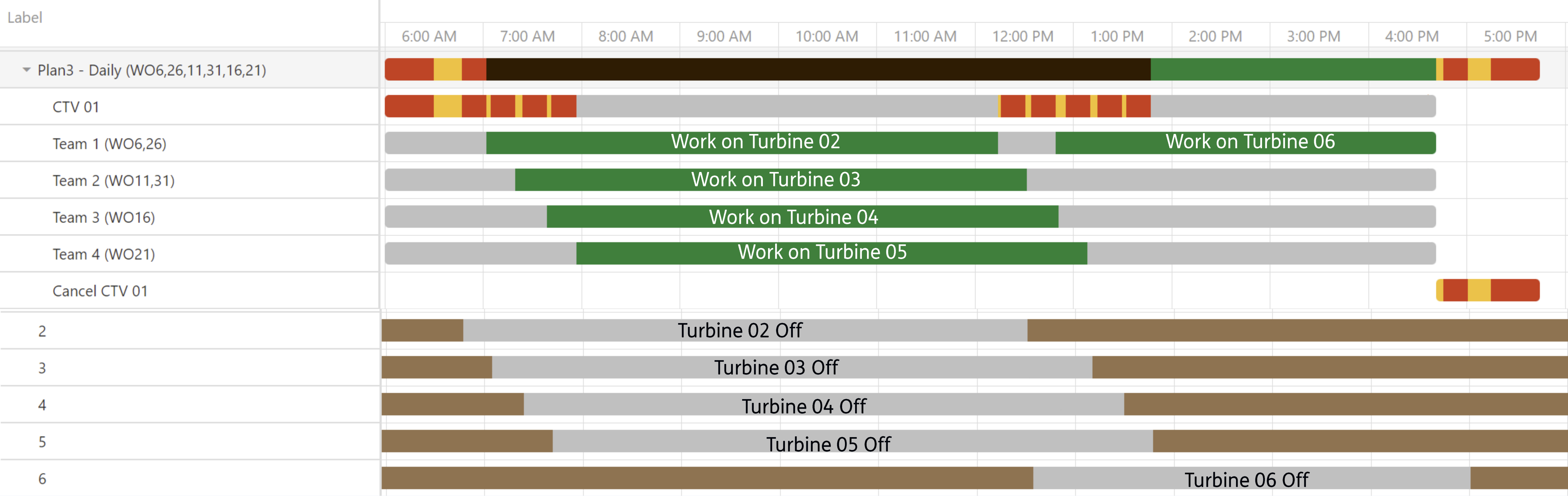
Ad-Hoc Delivery Time-Saving Estimation (IJV)

Conventional				Cargo Drone - Supported			
#	Step	Duration		#	Step	Duration	
1	CTV travels to SOV & pick up tools & spare parts	~20 min*	80min	1	Pick up tools & spare parts to CD	5 min	~10min
2	Transfer cargos from SOV to CTV	15 min		2	Cargo drone travels to WTG	~5 min	
3	CTV travels to WTG	~10 min		3	Cargo drone transfer cargos directly onto nacelle	2 min	
4	Transfer crew and cargos from CTV to WTG working platform	15 min					
5	Transfer technician crew and tools from WTG working platform to nacelle	20 min					

- Assume CTV travels at average speed of 10m/s (20knot), and cargo drone travels at 20m/s (40 knot)
- For step 1 in conventional case, the duration could also be as long as 1.5h if there is longer delay on CTV or traveling far away in the a farm. For now, the averege circumstance is considered (~20min), where stochatically duration can be considered in the future study.

Appendix B

Example of Corrective Maintenance Planning



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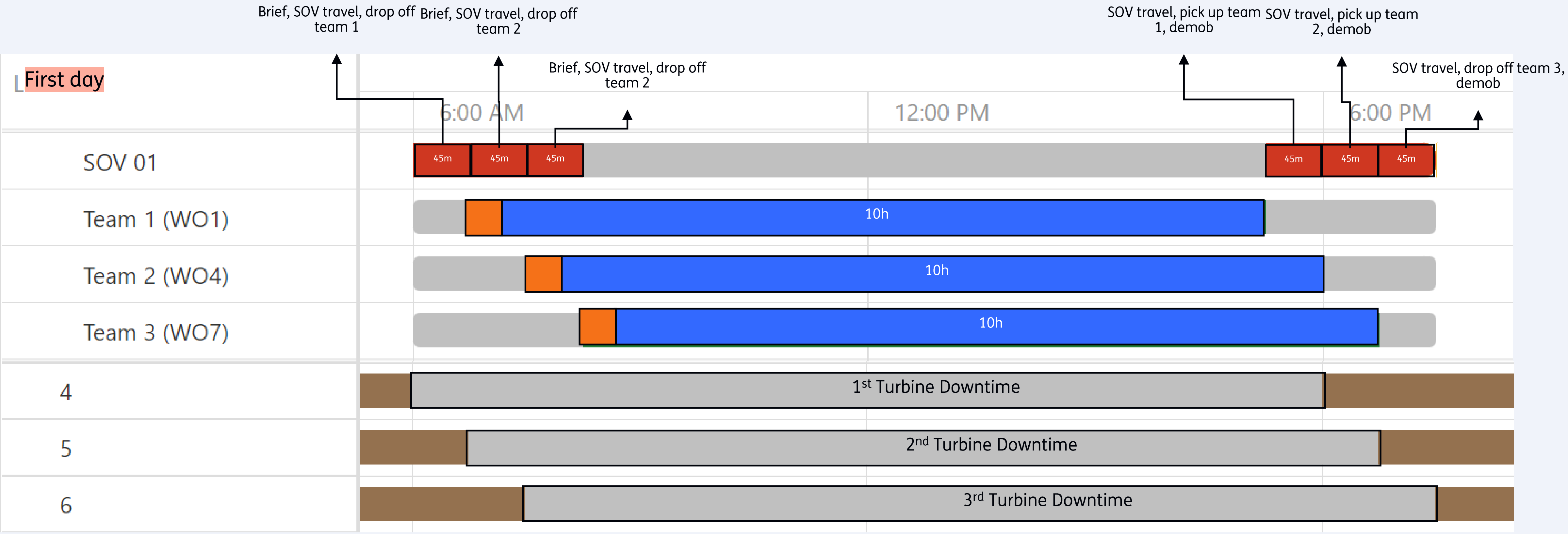
Example of Scheduled Maintenance Planning



Transfer cargos between TP and Nacelle, only on 1st and 3rd day   Actual Work