

Techno-economic analysis

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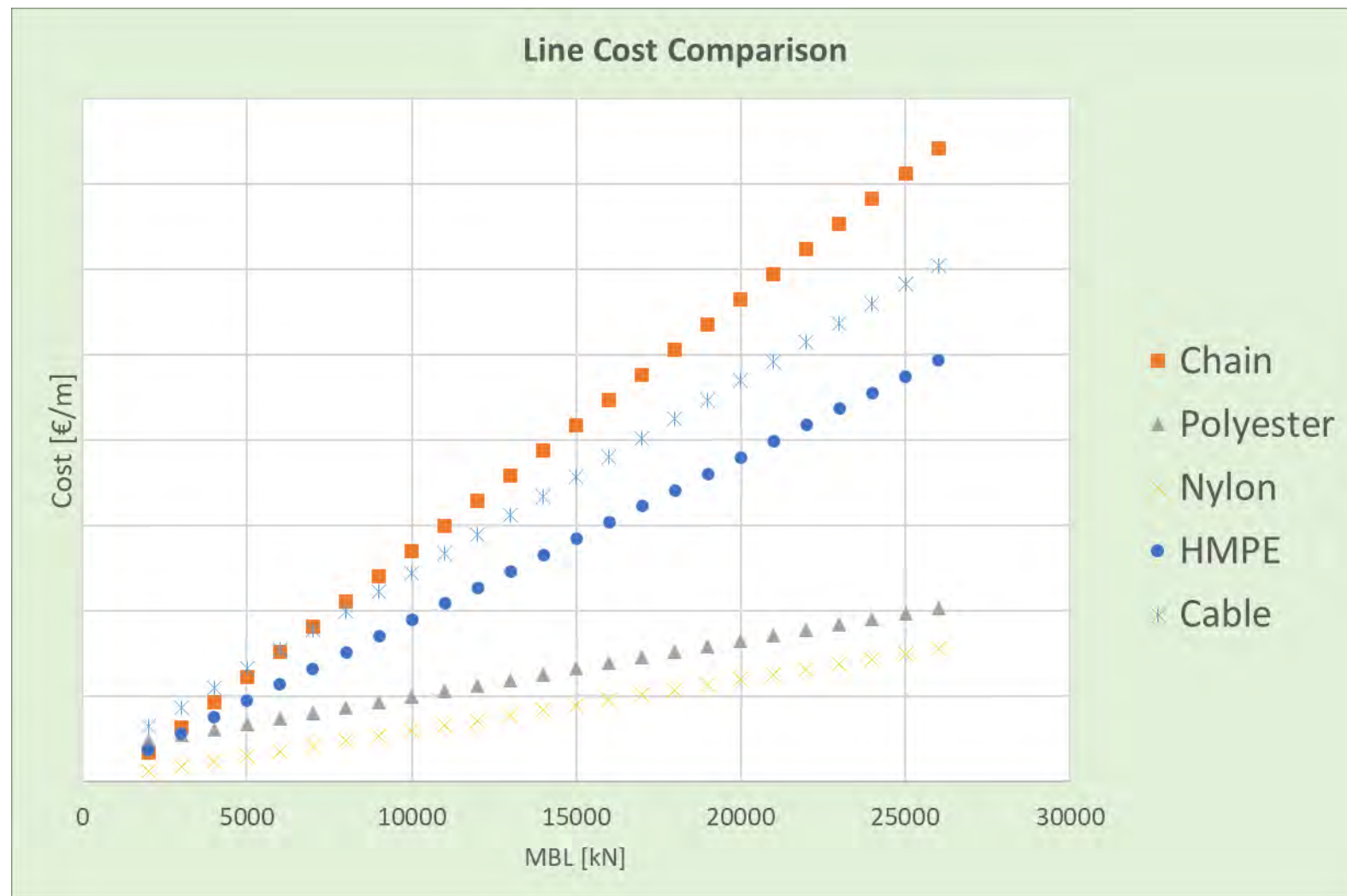
- Main findings and challenges identified in the literature
- Cost functions
- Case studies
- General conclusions



- **Only pile and suction piles** can be used as shared anchors
- **Anchor position** is imposed in shared configuration > It may increase line length compared to unshared configurations
- **Number of anchors** are reduced thus installation, inspection, maintenance and decommissioning are positively impacted
- **Mooring or FOWT failure** will have more consequences on shared anchors > Failure could impact several FOWT linked to the same anchor
- **Risk is increased** in case of failure, thus frequency of inspection shall be increased

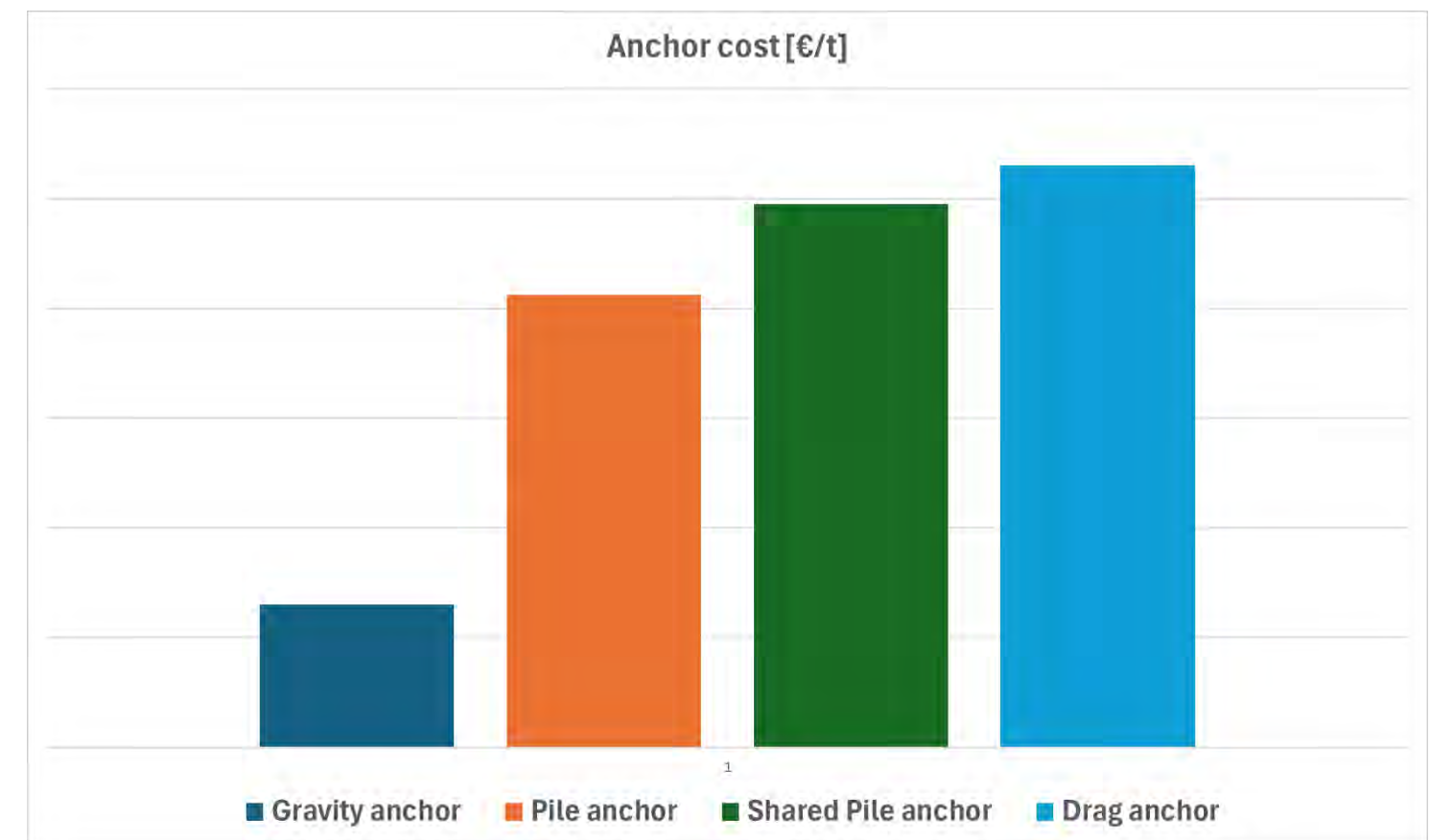
- Mooring lines

$$C_{Line} = C_1 * MBL + C_2$$



- Anchors

- Drag and pile anchor designed based on ABS
- Sensibility performed on SF for shared anchors between 1.2 and 1



[2] DTO_WP4_ECD_D4.6.pdf, Framework for the prediction of the reliability, economic and environmental criteria and assessment methodologies for moorings and foundations, 2015

• Unshared anchors

○ Drag and gravity anchor

$$C_{installation} = C_{mob} + C_{geo}N_{anchor} + C_{vessel}t_{ins\ anchor}(1 + percentage_{additional})N_{anchor} + C_{vessel}t_{ins\ line}(1 + percentage_{additional})N_{line}$$

○ Suction pile

$$C_{installation} = C_{mob} + C_{geo}N_{anchor} + (C_{vessel} + C_{ROV})t_{ins\ anchor}(1 + percentage_{additional})N_{anchor} + C_{vessel}t_{ins\ line}(1 + percentage_{additional})N_{line}$$

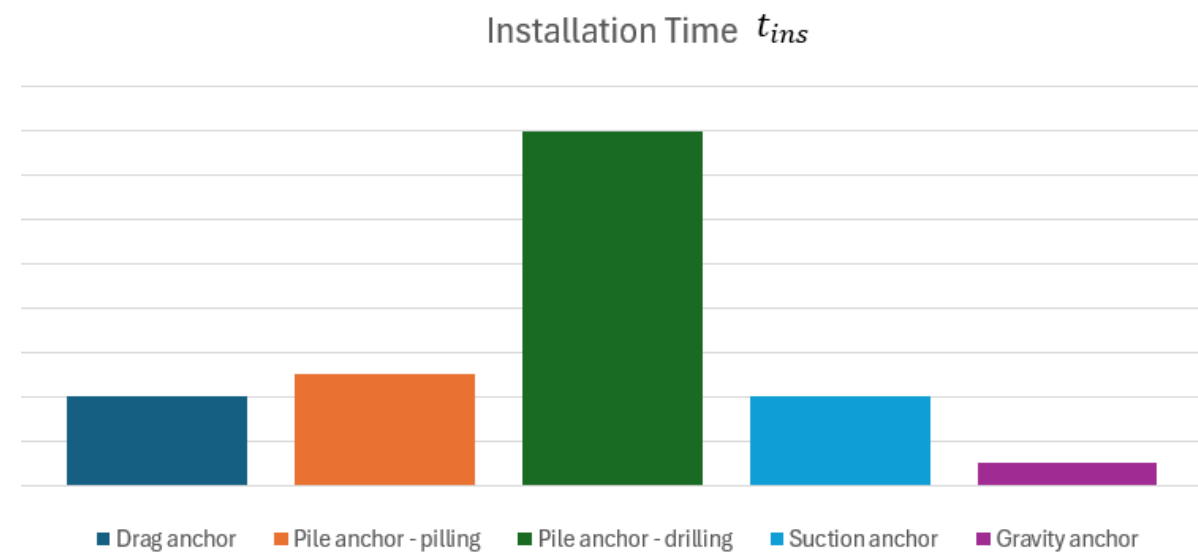
○ Driven pile

$$C_{installation} = C_{mob} + C_{geo}N_{anchor} + (C_{vessel} + C_{barge})t_{ins\ anchor}(1 + percentage_{additional})N_{anchor} + C_{vessel}t_{ins\ line}(1 + percentage_{additional})N_{line}$$

• Shared anchors

○ Addition of extra time due to complexity of shared anchor, example of the driven pile

$$C_{installation} = C_{mob} + C_{geo}N_{anchor} + \left((C_{vessel} + C_{barge})t_{ins\ anchor}(1 + percentage_{additional})N_{anchor}(1 + percentage_{add.\ shared}) \right) + C_{vessel}t_{ins\ line}(1 + percentage_{additional})N_{line}$$



Parameter	Symbol	Unit
Geotechnical investigation	C_{geo}	k€/anchor
Mobilization cost	C_{mob}	k€
AHV	C_{vessel}	k€/day
Transportation barge	C_{barge}	k€/day
ROV	C_{ROV}	k€/day
Additional cost	$percentage_{additional}$	%
Additional cost for shared anchor	$percentage_{add.\ shared}$	%
Installation time for line	$t_{ins\ line}$	h

- **Cost function**

$$C_{maintenance} = C_{vessel} \times f_{inspection\ anchor} (1 + percentage_{additional}) \times t_{life} \times N_{anchor} \times t_{anchor} + C_{vessel} \times f_{inspection\ line} (1 + percentage_{additional}) \times t_{life} \times N_{line} \times t_{line} + C_{mob} \times t_{life} \times \max(f_{inspection\ anchor}, f_{inspection\ line})$$

- **Sub parameters for all anchor types (1)**

Parameter	Symbol	unshared	Shared	Unit
Vessel mob/demob cost	C_{mob}	***		€
Vessel cost	C_{vessel}	***		€/day
Inspection time	t_{anchor}/t_{line}	***		day / Line
Inspection frequency anchor	$f_{inspection\ anchor}$	simple	double	/years
Inspection frequency line	$f_{inspection\ line}$	***		/years
Life time	t_{life}	***		years
Additional costs	$percentage_{additional}$	***		%

- **Cost function:**

- **Repair cost line / anchor**

$$C_{Repair\ line/anchor} = C_{mob} \times t_{life} \times failure_{rate} + C_{vessel}(1 + percentage_{additional}) \times t_{repair} \times failure_{rate} \times t_{life} + C_{repair} \times failure_{rate} \times t_{life}$$

- **Replacement cost unshared anchors**

$$C_{Replacement\ anchor} = C_{mob} \times t_{life} \times replacement_{rate} + (C_{anchor} + C_{vessel} (1 + percentage_{additional}) \times (t_{ins\ anchor} + t_{dismantelement} + t_{ins\ line})) \times replacement_{rate} \times t_{life}$$

- **Replacement cost shared anchors**

$$C_{Replacement\ anchor} = C_{mob} \times t_{life} \times replacement_{rate} + (C_{anchor} + C_{vessel} (1 + percentage_{add.}) \times (1 + percentage_{add.shared}) \times (t_{ins\ anchor} + t_{dismantelement} + t_{ins\ line} \times N_{line\ per\ anchor})) \times replacement_{rate} \times t_{life}$$

- **Rk for suction anchor:**

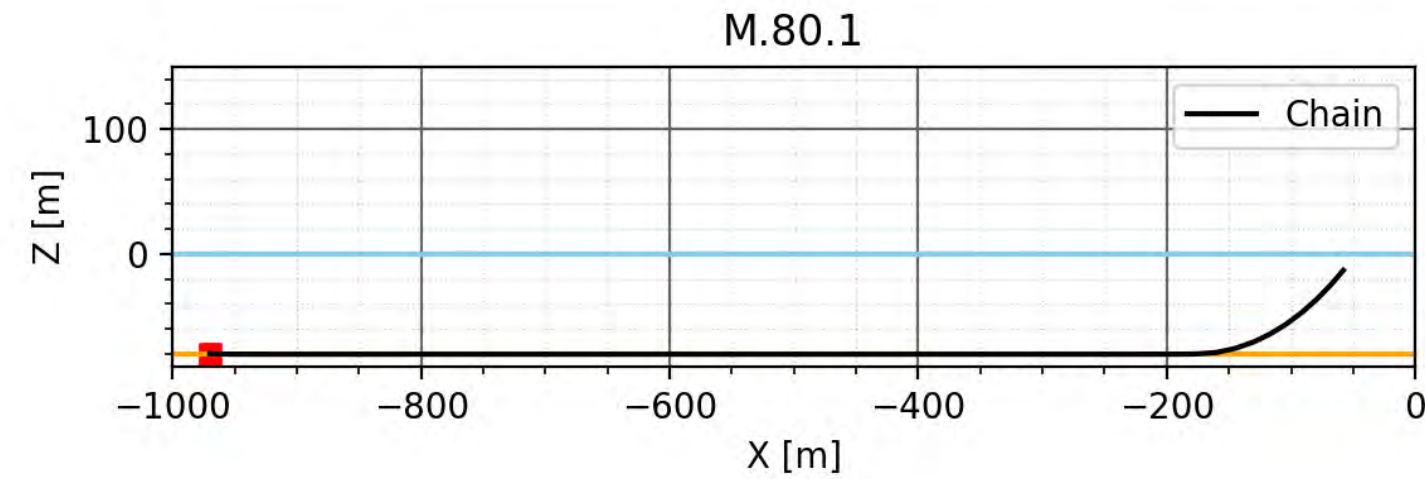
$$C_{vessel} = C_{vessel} + C_{ROV}$$

- **Sub parameters for all anchor types (1) :**

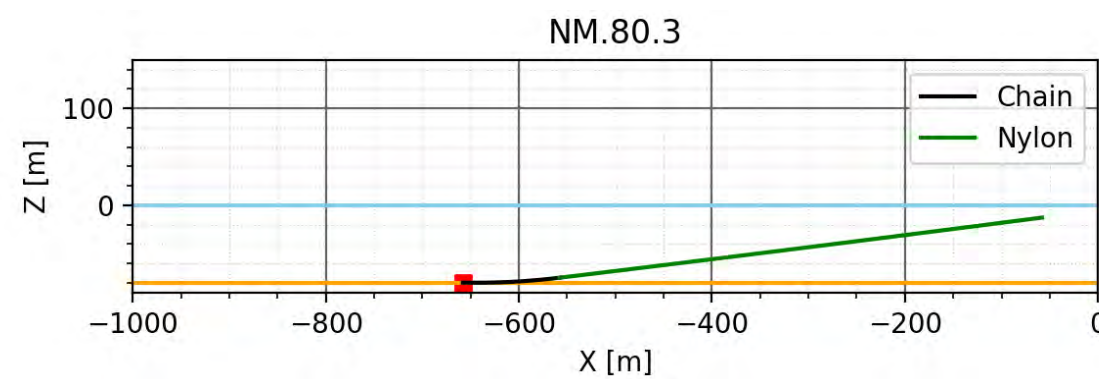
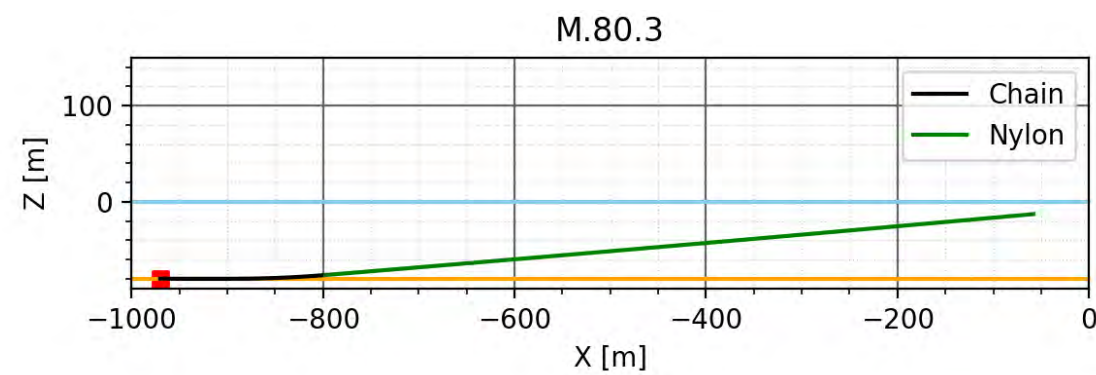
(1) Values based on Corewind deliverable D4.2

Parameter	Symbol	Value	Unit
Vessel mob/demob cost	C_{mob}	fixed	€
vessel day rate	C_{vessel}	fixed	€/day
repairs cost	C_{repair}	fixed	€/line
failure rate	$failure_{rate}$	fixed	/years
replacement rate	$replacement_{rate}$	fixed	/years
Life time	t_{life}	fixed	years
repair time	t_{repair}	fixed	day / Line
Cost line	C_{line}	Configuration dependant	€
Cost anchor	C_{anchor}	Configuration dependant	€
Installation time anchor	$t_{ins\ anchor}$	Configuration dependant	day
Dismantling time	$t_{dismantling}$	Configuration dependant	day
Installation time line	$t_{ins\ line}$	Configuration dependant	day
additional costs	$percentage_{additional}$	fixed	%

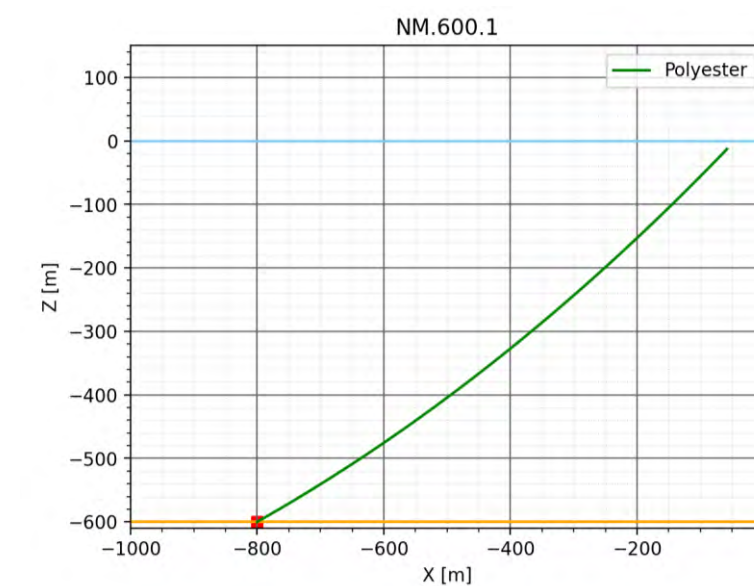
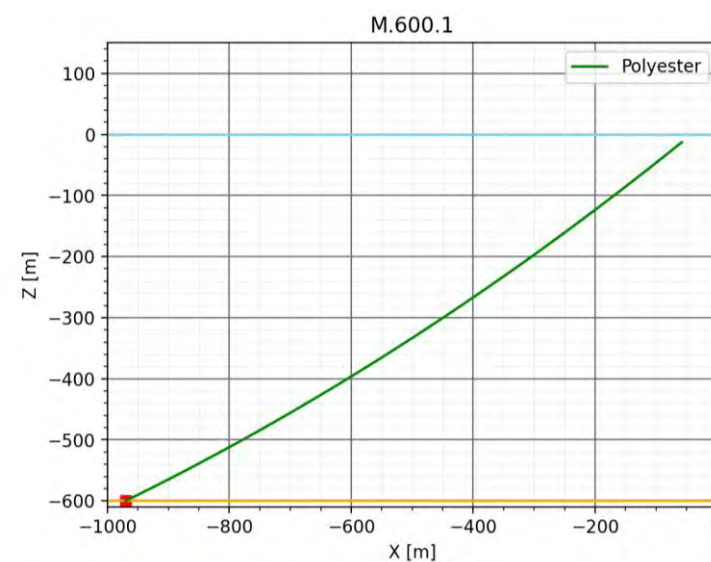
- **Case1:** WD=80m, Catenary, Chain



- **Case2:** WD=80m, Catenary, Chain + Nylon

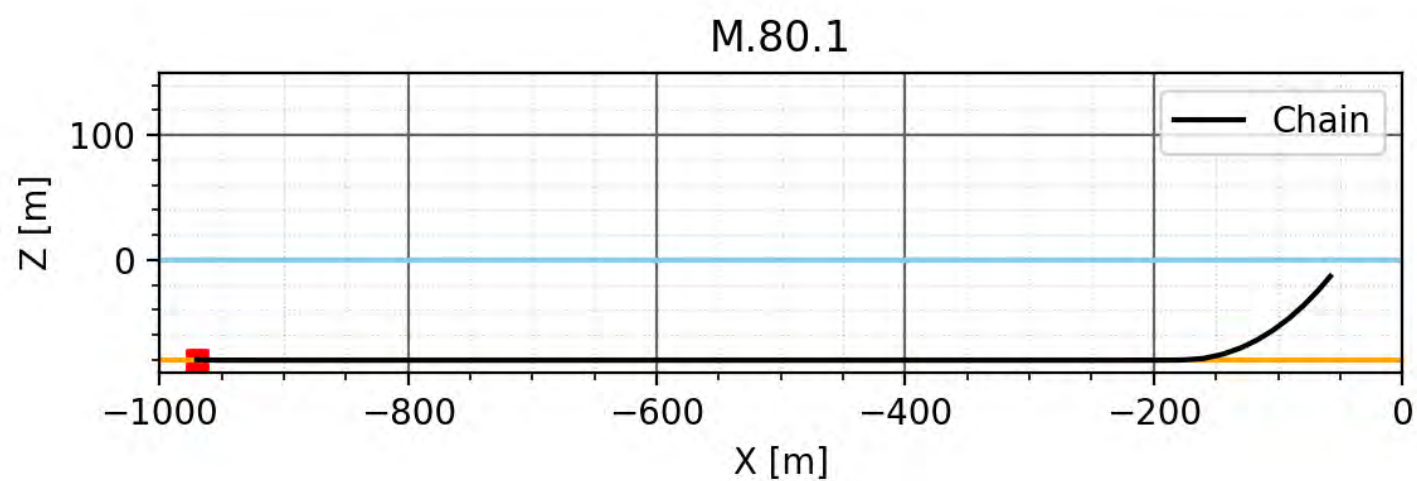


- **Case3:** WD=600m, Taut, Polyester



Case 1: Catenary chain in 80m water depth

Variable	Unit	Study 1 - 80.1				
		shared	unshared	shared	unshared	unshared
Water depth	[m]	80	80	80	80	80
Number of FOWT	[-]	100	100	100	100	100
Type of mooring	[-]	Catenary	Catenary	Catenary	Catenary	Catenary
Mooring lines materials	[-]	Chain	Chain	Chain	Chain	Chain
Type of anchors	[-]	Driven piles	Driven piles	Driven piles	Driven piles	Drag
Number of anchors	[-]	100	300	100	300	300
Type of seabed	[-]	Sand	Sand	Sand	Sand	Sand
Line length (compare to Ref)	[m]	0%	Ref	0%	0%	0%
MBL (compare to Ref)	[kN]	0%	Ref	0%	0%	0%
Anchors Ultimate Holding Capacity (compare to ref)	[kN]	2%	Ref	2%	0%	0%
Anchor installation type (for driven pile)		hammer	hammer	drilling	drilling	



$$\frac{Ref - Value}{Value}$$



Shared and unshared mooring line configurations are identical

Case 1 – Compared to hammer installation

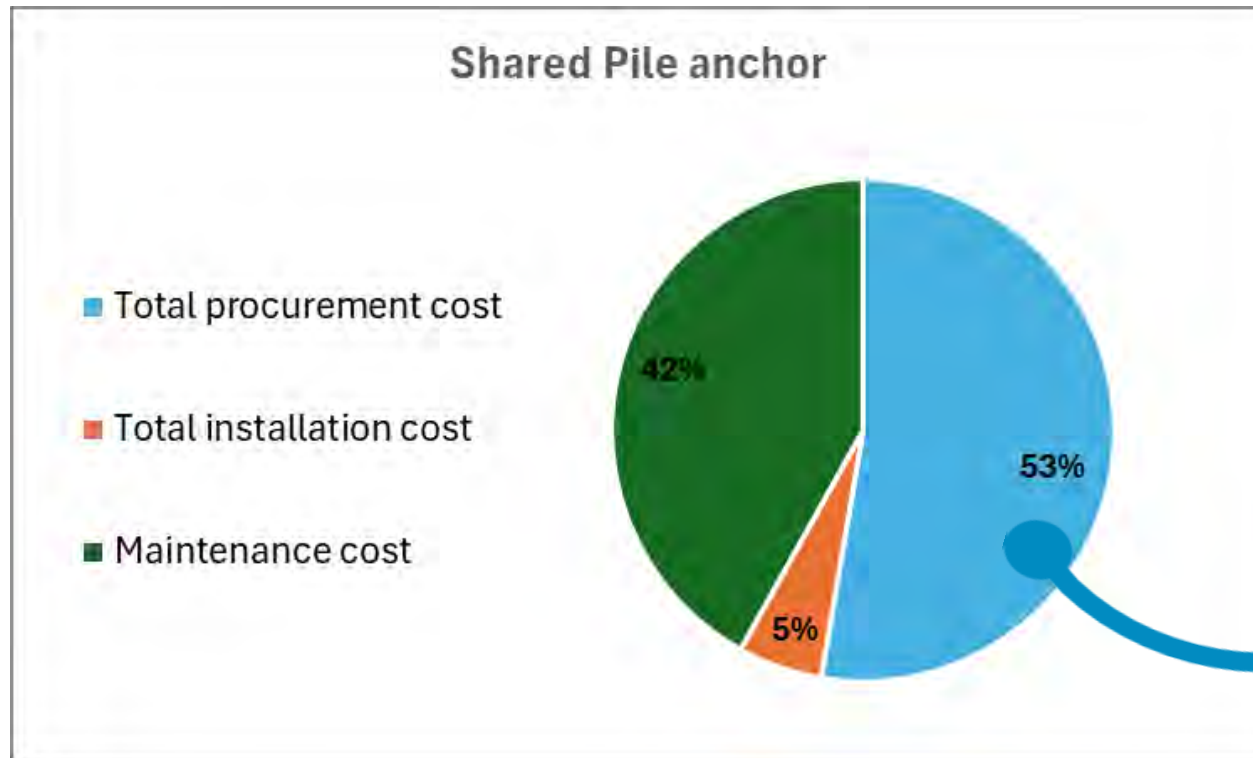
Variable	Unit	Study 1 - 80.1		
		Shared - Pile	Unshared - Pile	Unshared - Drag
Water depth	[m]	80	80	80
Number of FOWT	[-]	100	100	100
Type of mooring	[-]	Catenary	Catenary	Catenary
Mooring lines materials	[-]	Chain	Chain	Chain
Type of anchors	[-]	Driven piles	Driven piles	Drag
Number of anchors	[-]	100	300	300
Type of seabed	[-]	Sand	Sand	Sand
Line length (Compared to Ref)	[m]	Ref	0%	0%
MBL (Compared to Ref)	[kN]	Ref	0%	0%
Anchor installation type (for pile)		Hammer	Hammer	
Mooring system procurement and installation cost	[% of NM]	Ref	-11.7%	-10.2%
Mooring line and anchor inspection cost including mob and demob	[% of NM]	Ref	-15.8%	-15.8%
repairs, failure cost global cost	[% of NM]	Ref	-24.6%	-24.5%
Maintenance cost (include 2 above costs)	[% of NM]	Ref	-23.0%	-22.9%
Total cost reduction	[% of NM]	Ref	-16.8%	-16.0%



- Procurement cost reduced ~7%
- Installation cost reduced with smaller reduction for drag anchor as easier to install
- Overall global procurement and installation cost reduction ~12%
- Maintenance cost reduced ~23%
- Overall cost reduction ~16%

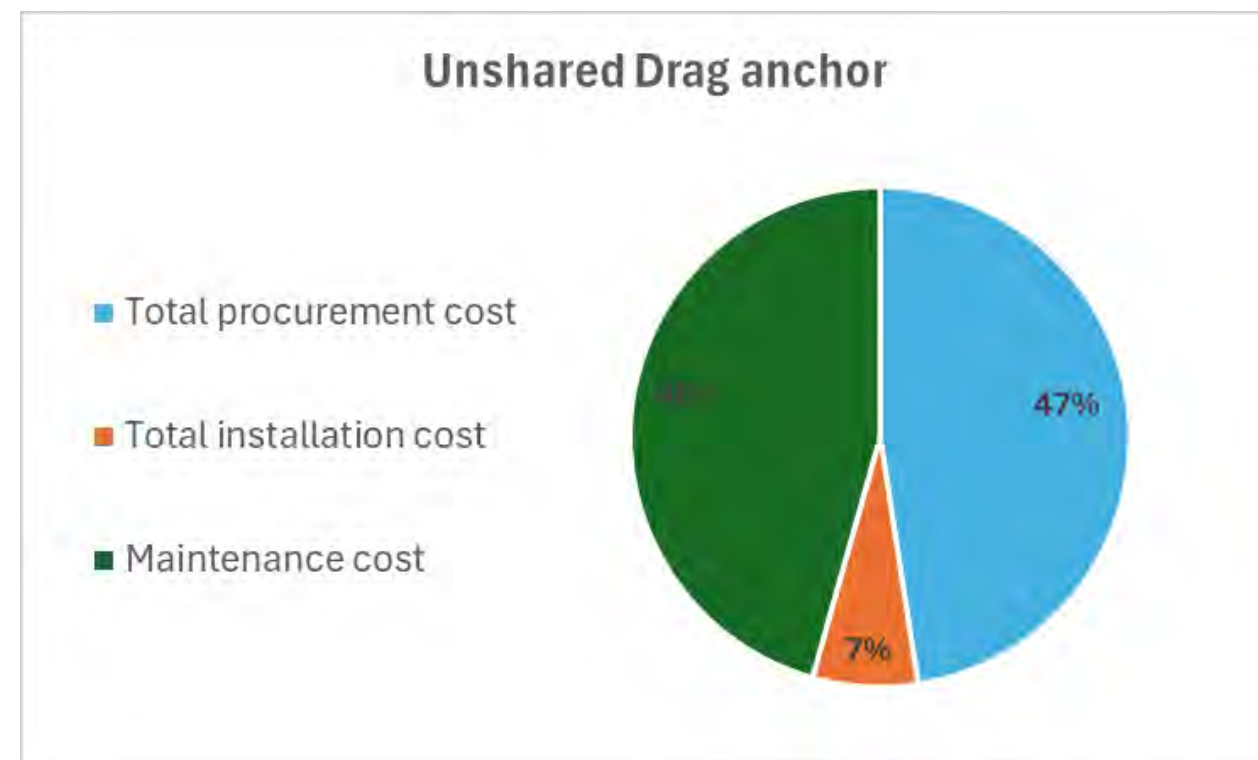
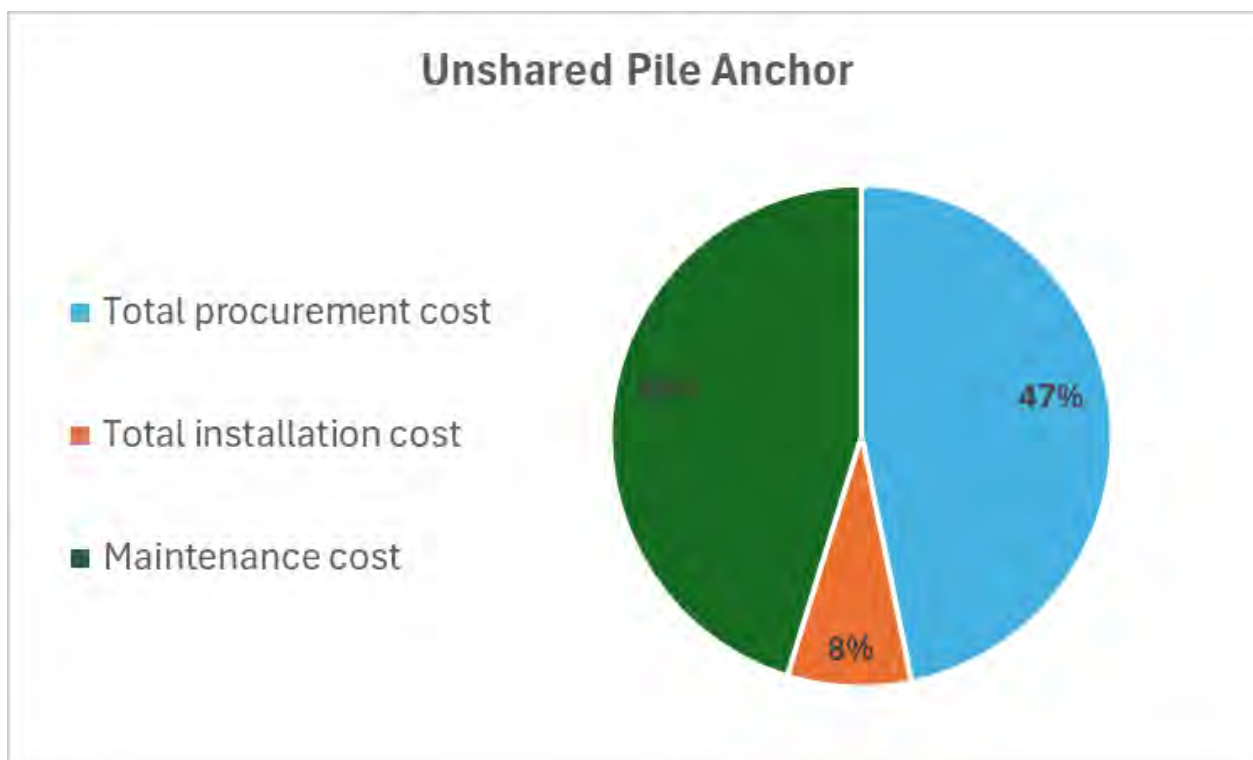
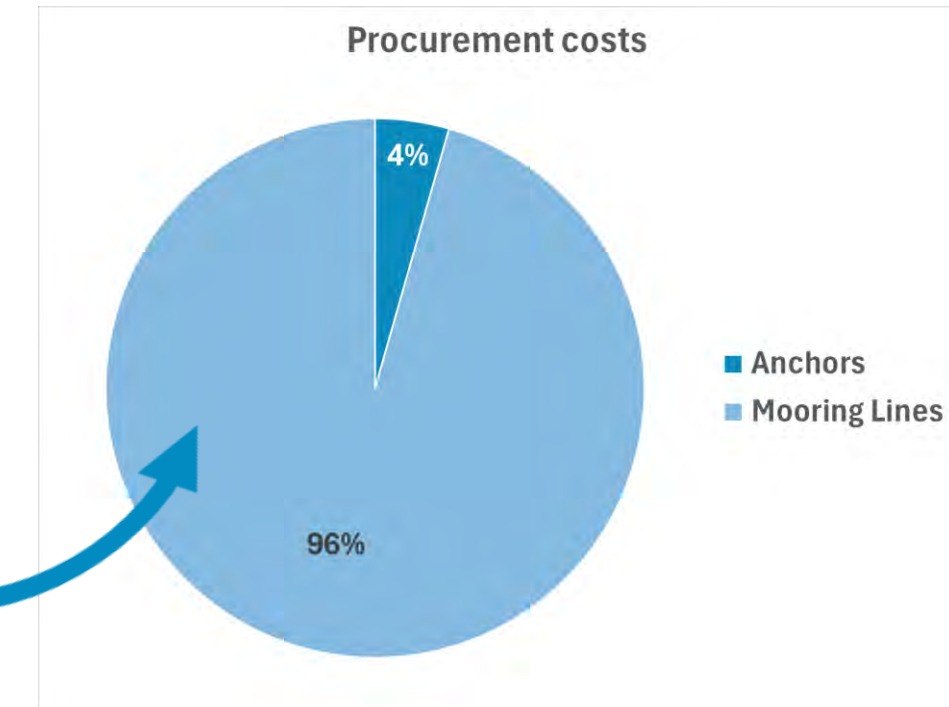
$$\frac{Cost_{ref} - Cost}{Cost}$$

Case 1 – Compared to hammer installation



Compared to unshared configurations

- Maintenance cost ratio is **reduced**
- Installation cost ratio is **reduced**
- Procurement cost ratio **increases**
- Procurement costs are governed by **mooring lines**



Case 1 – Safety factor impact



Variable	Unit	Study 1 - 80.1	
		Shared – Pile – SF = 1.2	Shared – Pile – SF = 1
Water depth	[m]	80	80
Number of FOWT	[-]	100	100
Type of mooring	[-]	Catenary	Catenary
Mooring lines materials	[-]	Chain	Chain
Type of anchors	[-]	Driven piles	Driven piles
Number of anchors	[-]	100	100
Type of seabed	[-]	Sand	Sand
Line length (Compared to Ref)	[m]	Ref	0%
MBL (Compared to Ref)	[kN]	Ref	0%
Anchor installation type (for pile)		Hammer	Hammer
Procurement costs	[% of NM]	Ref	0.77%
Installation costs	[% of NM]	Ref	0%
Maintenance costs	[% of NM]	Ref	0.24%
Total cost reduction	[% of NM]	Ref	0.51%

Minor influence of SF on global cost reduction

- Procurement cost reduction of 0.8 %
- Maintenance cost reduction -> negligible
- Global cost reduction 0.5 %
- When anchor procurement costs tend to be neglectable compared to other posts, safety factors applied on anchor design have a limited impact on global costs

Case 2: Catenary Chain + Nylon in 80m water depth

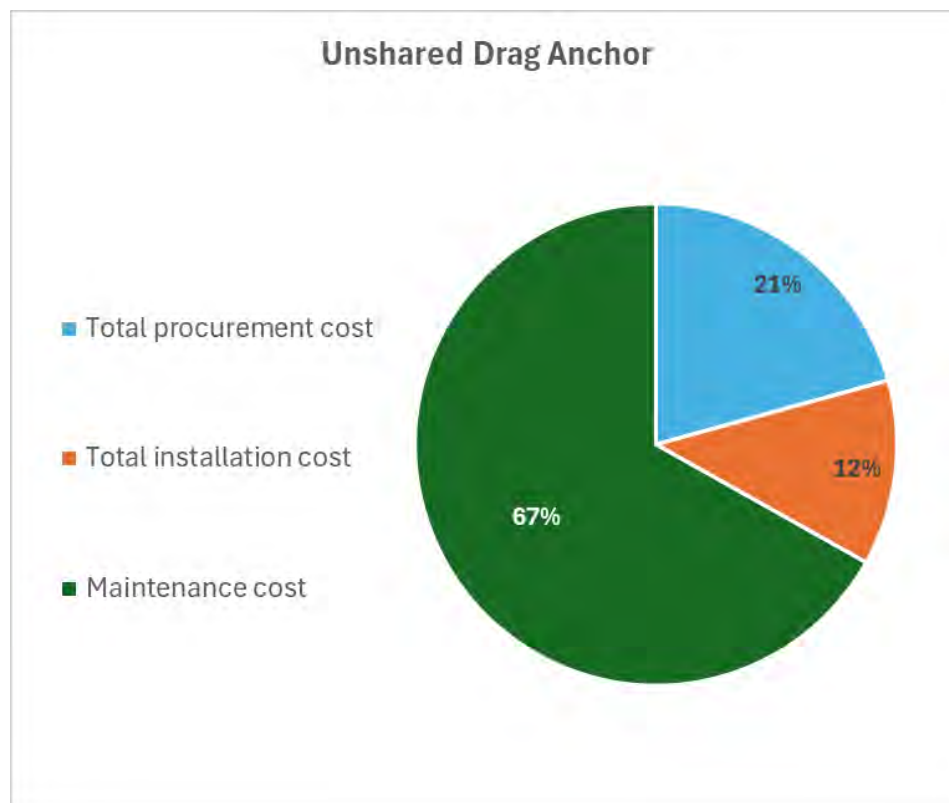
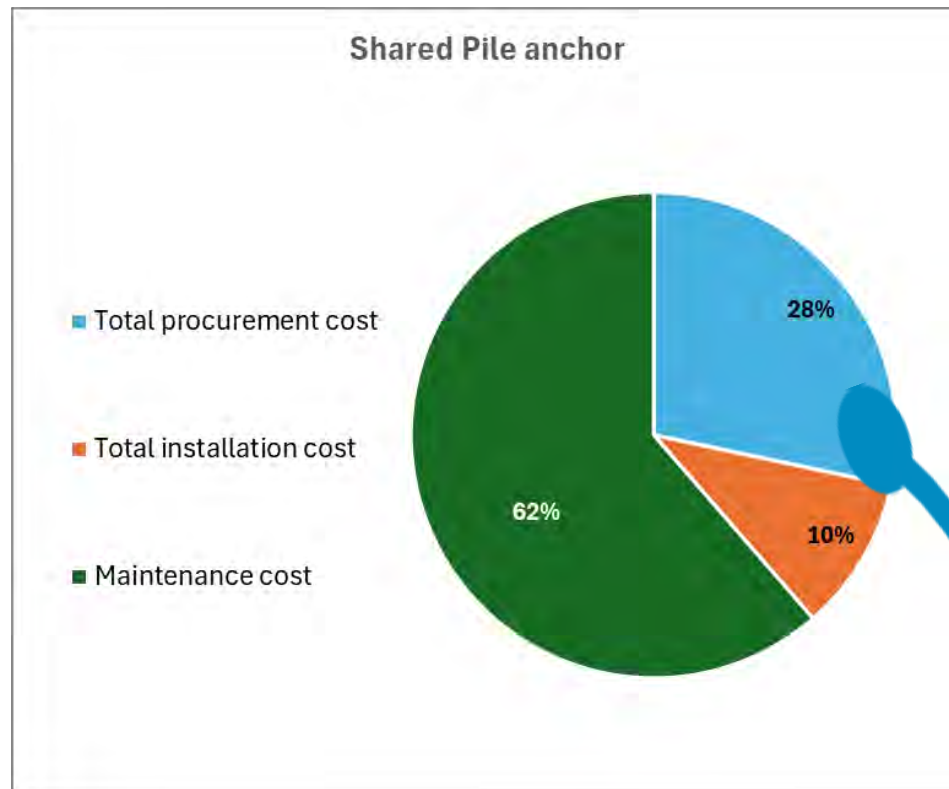


Variable	Unit	Study 2 - 80.3	
		Shared	Unshared
Water depth	[m]	80	80
Number of FOWT	[-]	100	100
Type of mooring	[-]	Catenary	Catenary
Mooring lines materials	[-]	Chain / Nylon	Chain / Nylon
Type of anchors	[-]	Driven piles	Drag
Number of anchors	[-]	100	300
Type of seabed	[-]	Sand	Sand
Line length	[m]	Ref	33 %
MBL	[kN]	Ref	-3.8 %
Anchor installation type (for pile)		Hammer	
Procurement Cost reduction	[% of NM]	Ref	11.1 %
Installation Cost reduction	[% of NM]	Ref	-33%
Procurement & Installation Cost reduction	[% of NM]	Ref	-2.9%
Maintenance Cost reduction	[% of NM]	Ref	-25.3%
Global Cost reduction	[% of NM]	Ref	-18.7%

- Procurement cost **not reduced** for shared anchor as mooring line length increased
- Installation cost **reduced** as seen in case1
- Overall procurement and installation cost **slightly reduced**
- Maintenance cost reduction around **25%**
- Overall total cost reduction **around 19%** with O&M main contributor

$$\frac{Cost_{ref} - Cost}{Cost}$$

Case 2: Catenary Chain + Nylon in 80m water depth

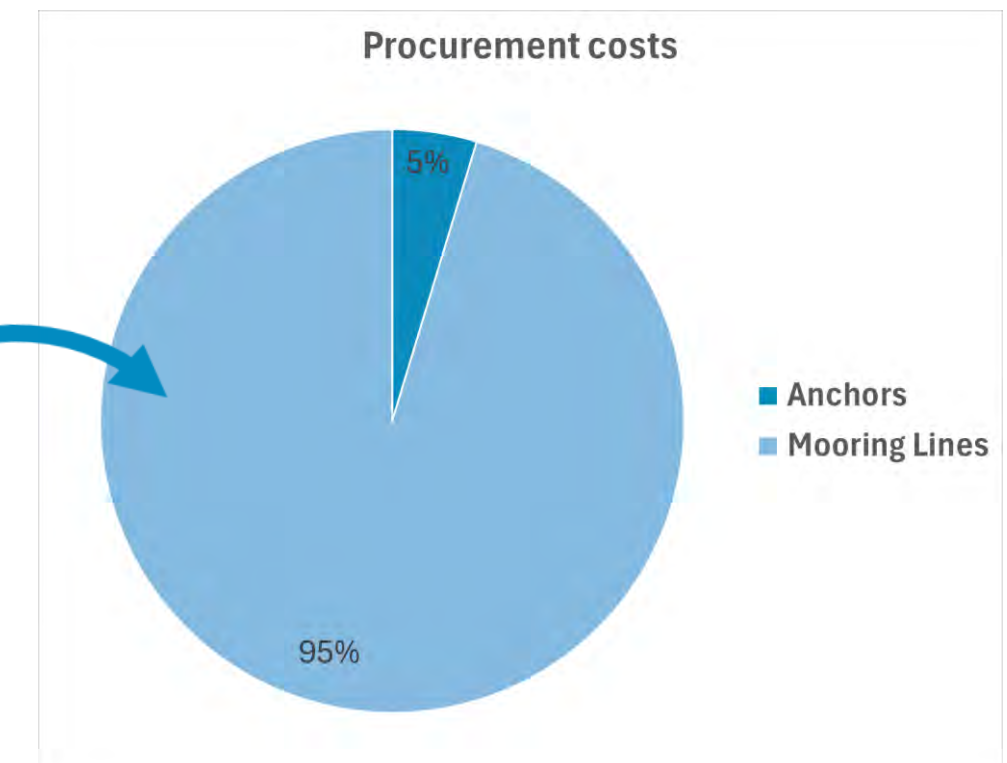
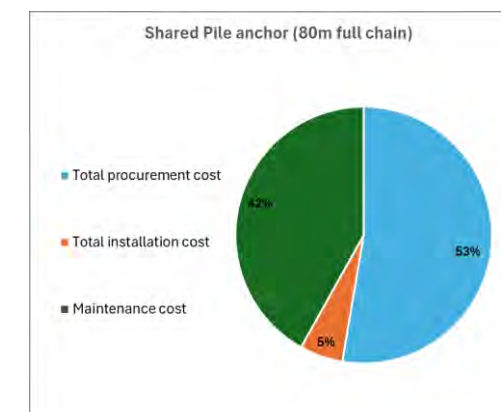


Compared to unshared configurations

- Maintenance cost ratio is reduced
- Installation cost ratio is reduced
- Procurement cost ratio increases
- Procurement costs are still governed by mooring lines

Compared to 80m full chain configuration

- Maintenance ratio increases

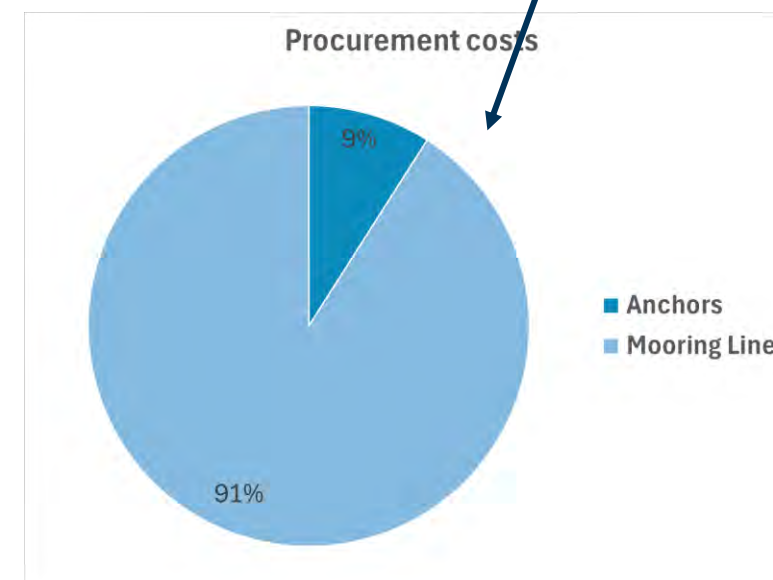
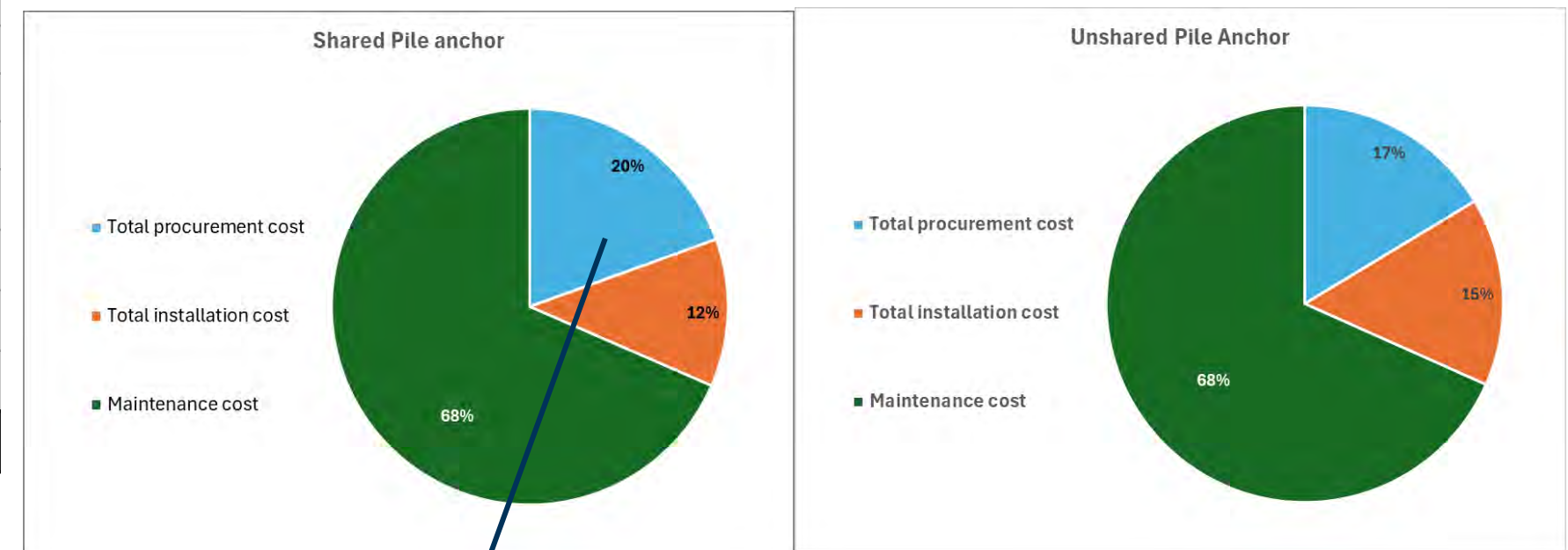


Case 3: Taut polyester in 600m WD

Variable	Unit	Study 3 - 600.1	
		Shared	Unshared
Water depth	[m]	600	600
Number of FOWT	[-]	100	100
Type of mooring	[-]	Taut	Taut
Mooring lines materials	[-]	Polyester	Polyester
Type of anchors	[-]	Driven piles	Driven piles
Number of anchors	[-]	100	300
Type of seabed	[-]	Sand	Sand
Line length	[m]	Ref	14%
MBL	[kN]	Ref	-10%
Anchor installation type (for pile)		hammer	hammer
Procurement Cost reduction	[% of NM]	Ref	-14.4%
Installation Cost reduction	[% of NM]	Ref	-43%
Procurement & Installation Cost reduction	[% of NM]	Ref	-28.4%
Maintenance Cost reduction	[% of NM]	Ref	-27.9%
Global Cost reduction	[% of NM]	Ref	-28.1%

$$\frac{Cost_{ref} - Cost}{Cost}$$

- Procurement cost reduced ~14%
- Installation cost reduced as seen in case1
- Overall procurement and installation cost reduced ~28%
- Maintenance cost reduction around 28%
- Overall total cost reduction around 28% with O&M main contributor

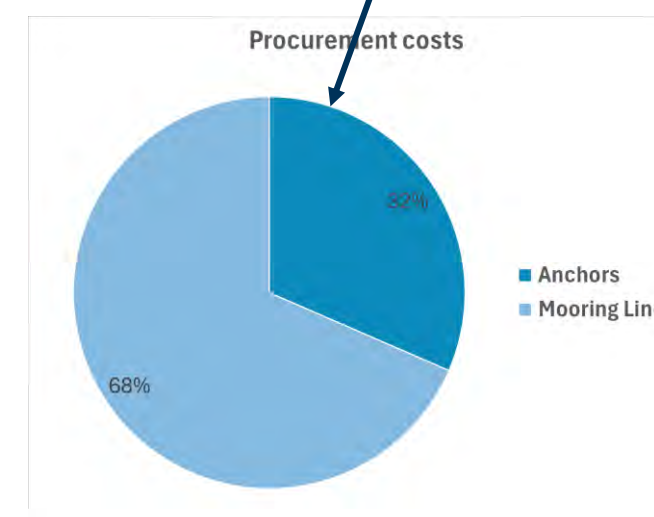
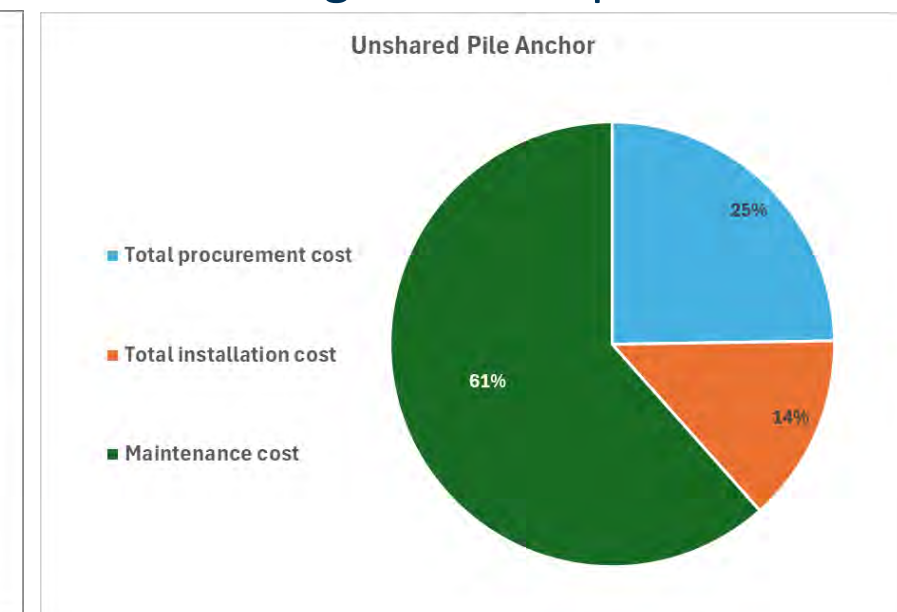
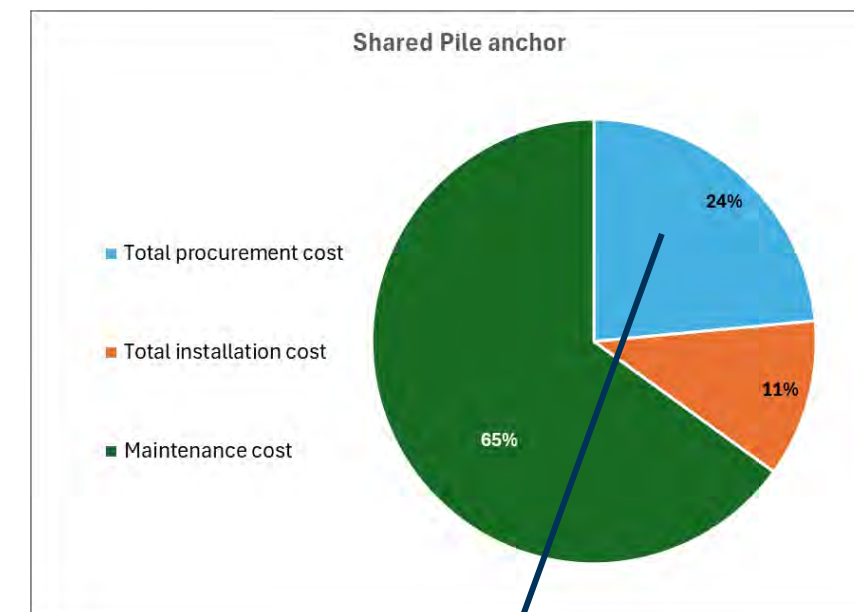


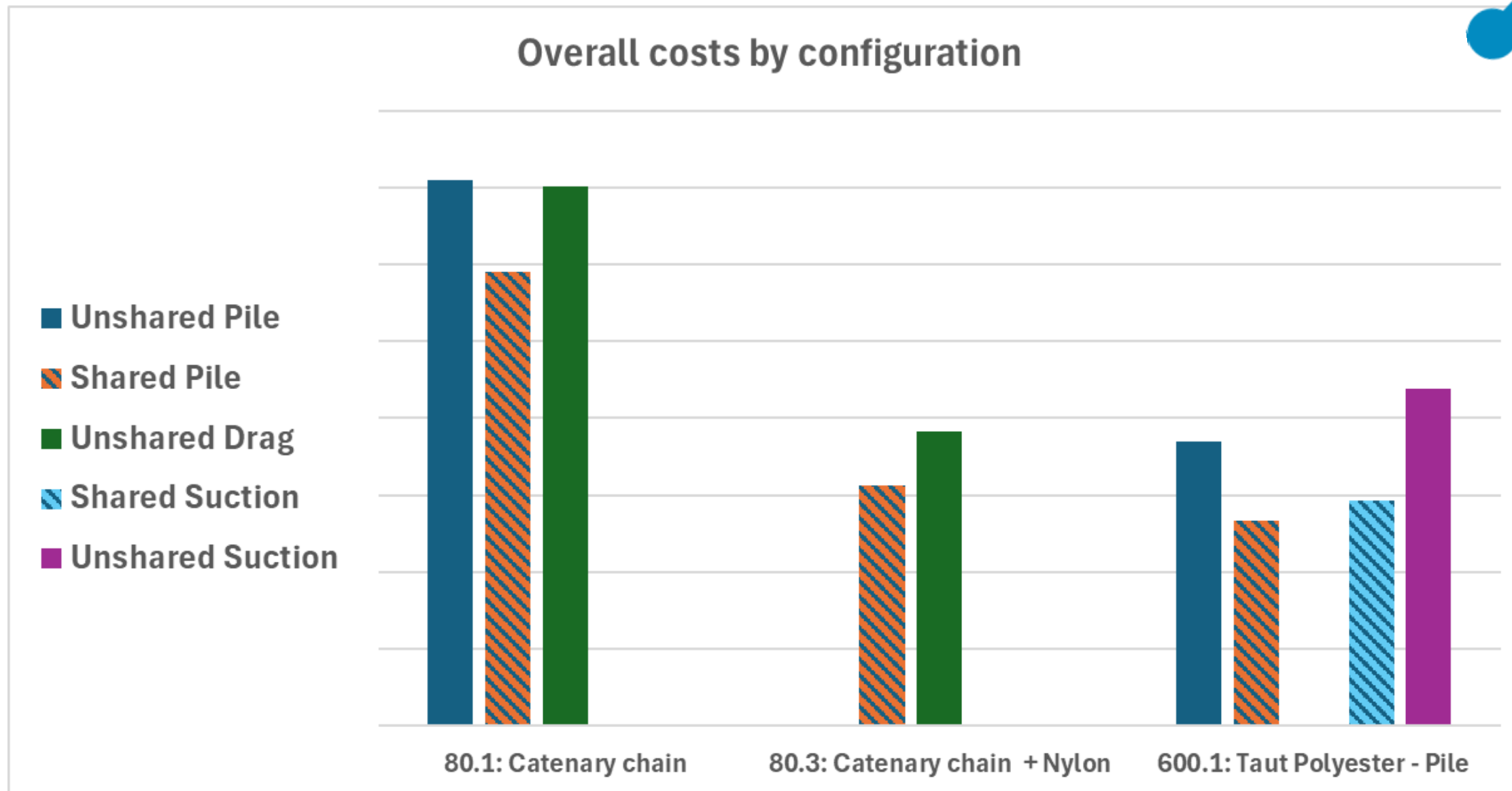
Case3: Taut polyester in 600m WD – Comparison with suction piles


Variable	Unit	Study 3 - 600.1	
		Shared	Unshared
Water depth	[m]	600	600
Number of FOWT	[-]	100	100
Type of mooring	[-]	Taut	Taut
Mooring lines materials	[-]	Polyester	Polyester
Type of anchors	[-]	Suction piles	Suction piles
Number of anchors	[-]	100	300
Type of seabed	[-]	Sand	Sand
Line length	[m]	Ref	14%
MBL	[kN]	Ref	-10%
Procurement Cost reduction	[% of NM]	Ref	-36.6%
Installation Cost reduction	[% of NM]	Ref	-44%
Procurement & Installation Cost reduction	[% of NM]	Ref	-39.2%
Maintenance Cost reduction	[% of NM]	Ref	-29.5%
Global Cost reduction	[% of NM]	Ref	-33.2%

$$\frac{Cost_{ref} - Cost}{Cost}$$

- Procurement cost reduction ~37%
- Installation cost reduction similar to comparison between 2 driven piles
- Maintenance cost reduction ~30%, highest reduction achieved due to anchor pricing
- Overall total cost reduction of 33%
 - Anchor cost is a crucial factor in reducing overall expenses





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- Shared anchors are **cost effective** compared to drag anchors that are cost effective compared to driven pile
 - Main cost reduction are obtained for **installation and maintenance**
 - Total cost main contributor is **maintenance**
 - Cost reduction **between 16 to 33%** are obtained for shared anchors
 - **Suction pile** leads to higher cost reduction than driven pile

Remarks:

- The inspection rate for shared anchors could be increased while still achieving cost reductions, as inspection costs represent a small portion of overall maintenance expenses
- Replacement costs could be optimized by accounting for production loss of the FOWT during downtime. This would help minimize differences between shared and unshared anchors, as a shared anchor failure impacts three FOWTs instead of one.
- Maintenance costs are significantly influenced by the failure rate, which could be higher or lower than assumed in this study, impacting overall cost outcomes.
- Knowledge transfer from geotechnical studies needs to be completed to refine Safety Factor definition applied on shared anchor costs