Mooring system design and anchor load analysis

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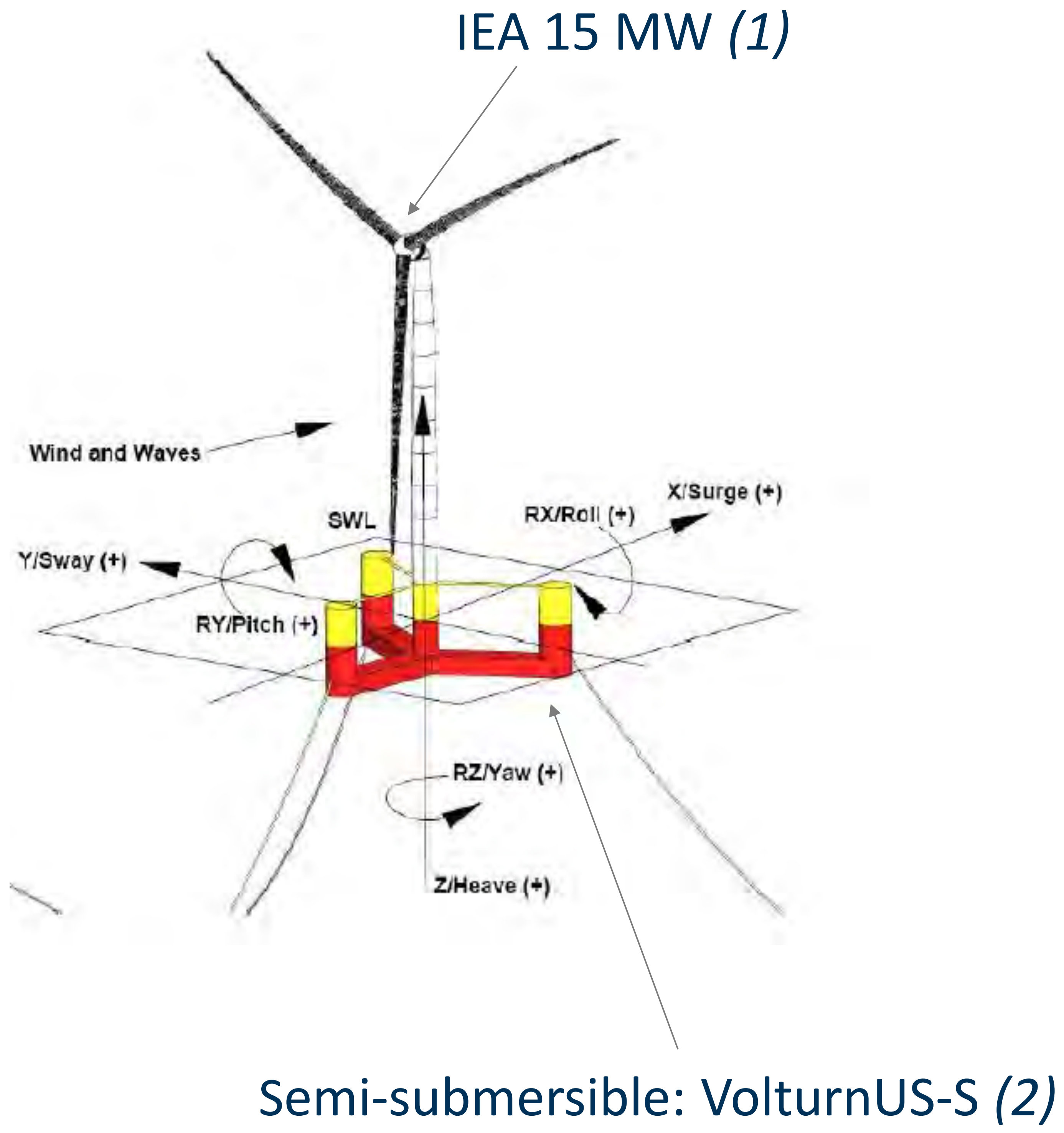
Objectives of the analysis

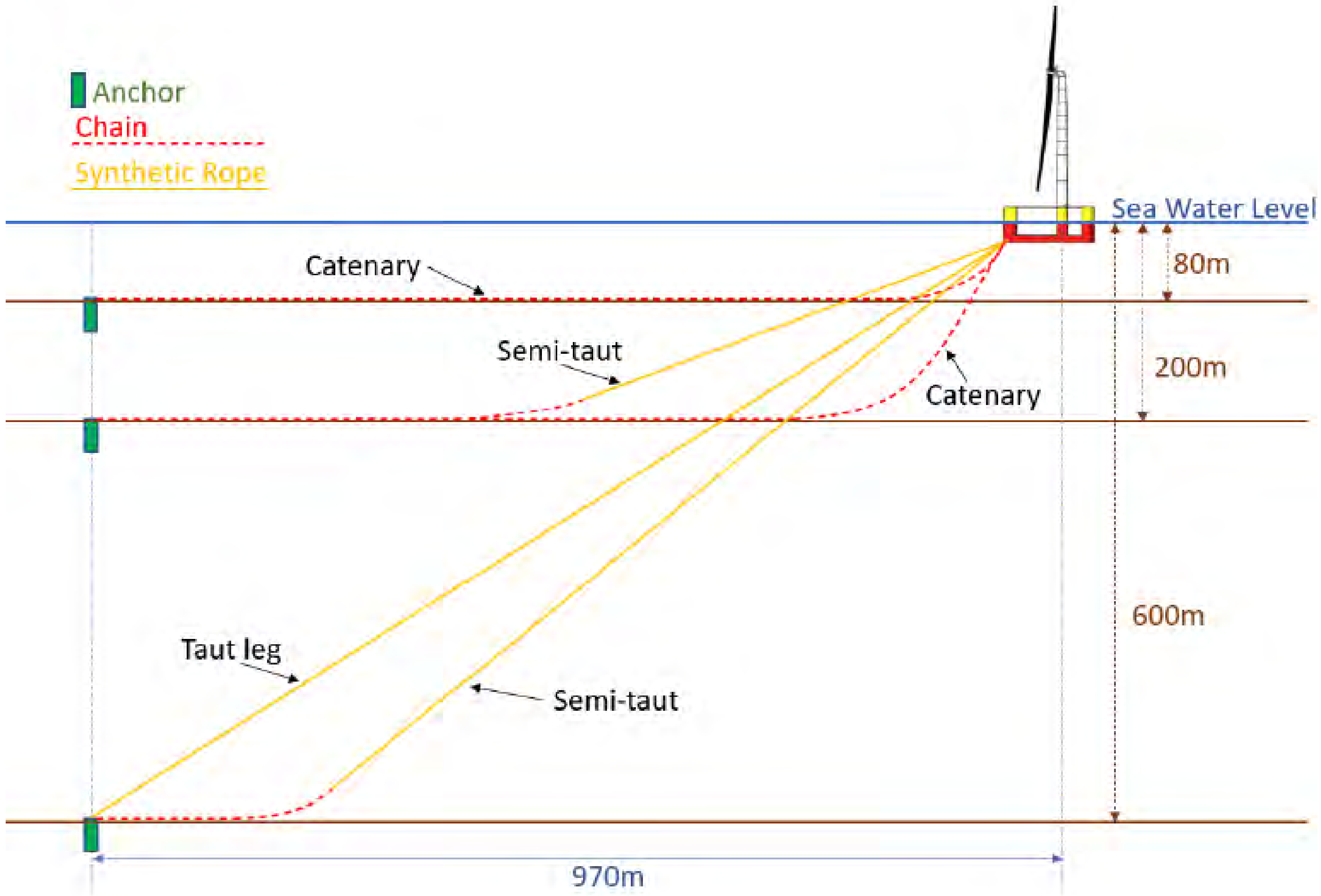
How does sharing anchors affect the feasibility, design, cost, and reliability of mooring systems for floating offshore wind farms?

- Numerical case studies involving a 15 MW turbine, a semi-submersible floater, and farm layouts 3 different water depths
- Mooring systems are designed with and without shared anchors
- Mooring loads analysis
- Anchor loads analysis
- Costs of shared vs. single-line anchors are compared

Picto credit: Dranan Endar/Noun Project

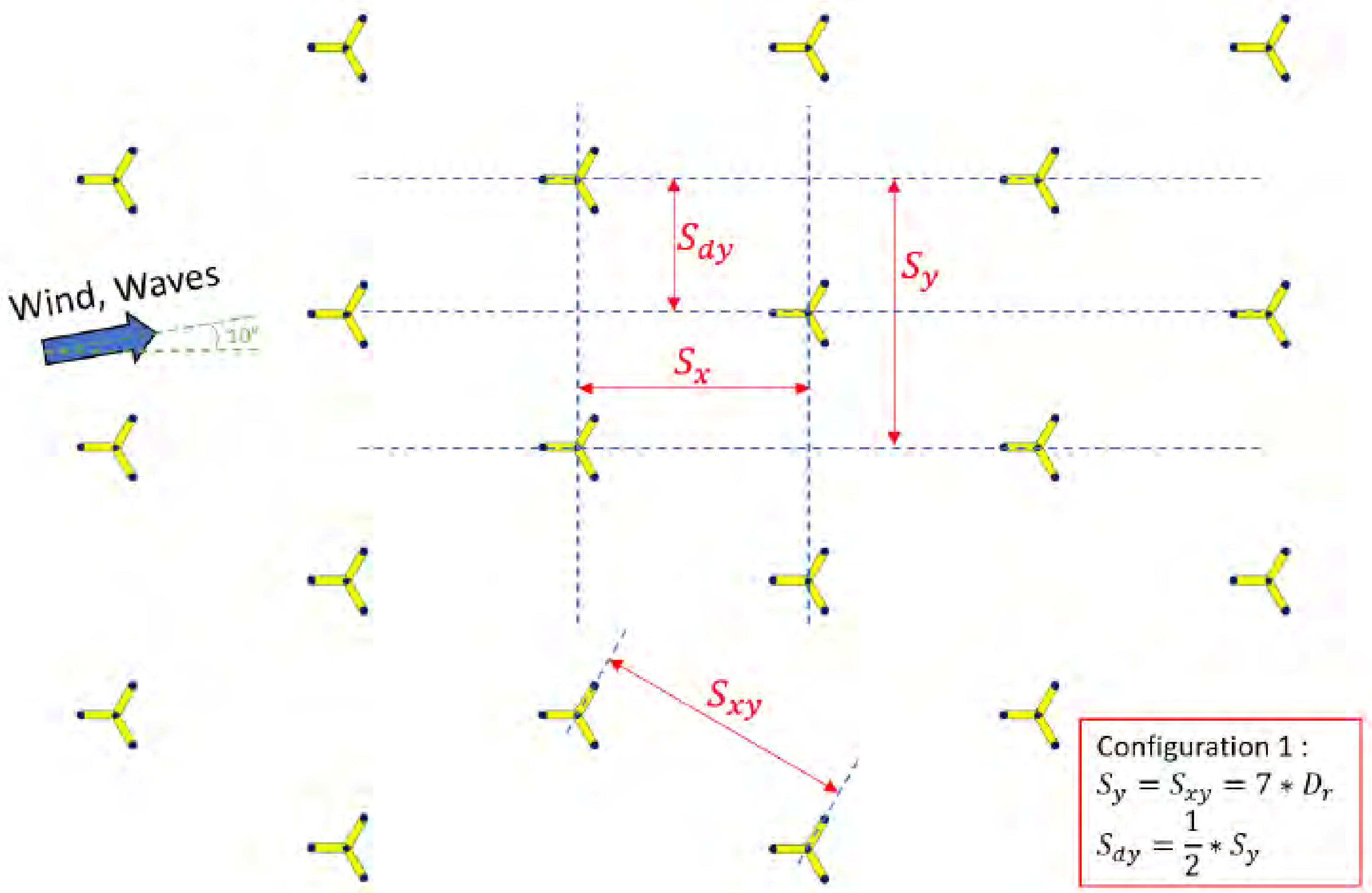
Design basis (1/5)

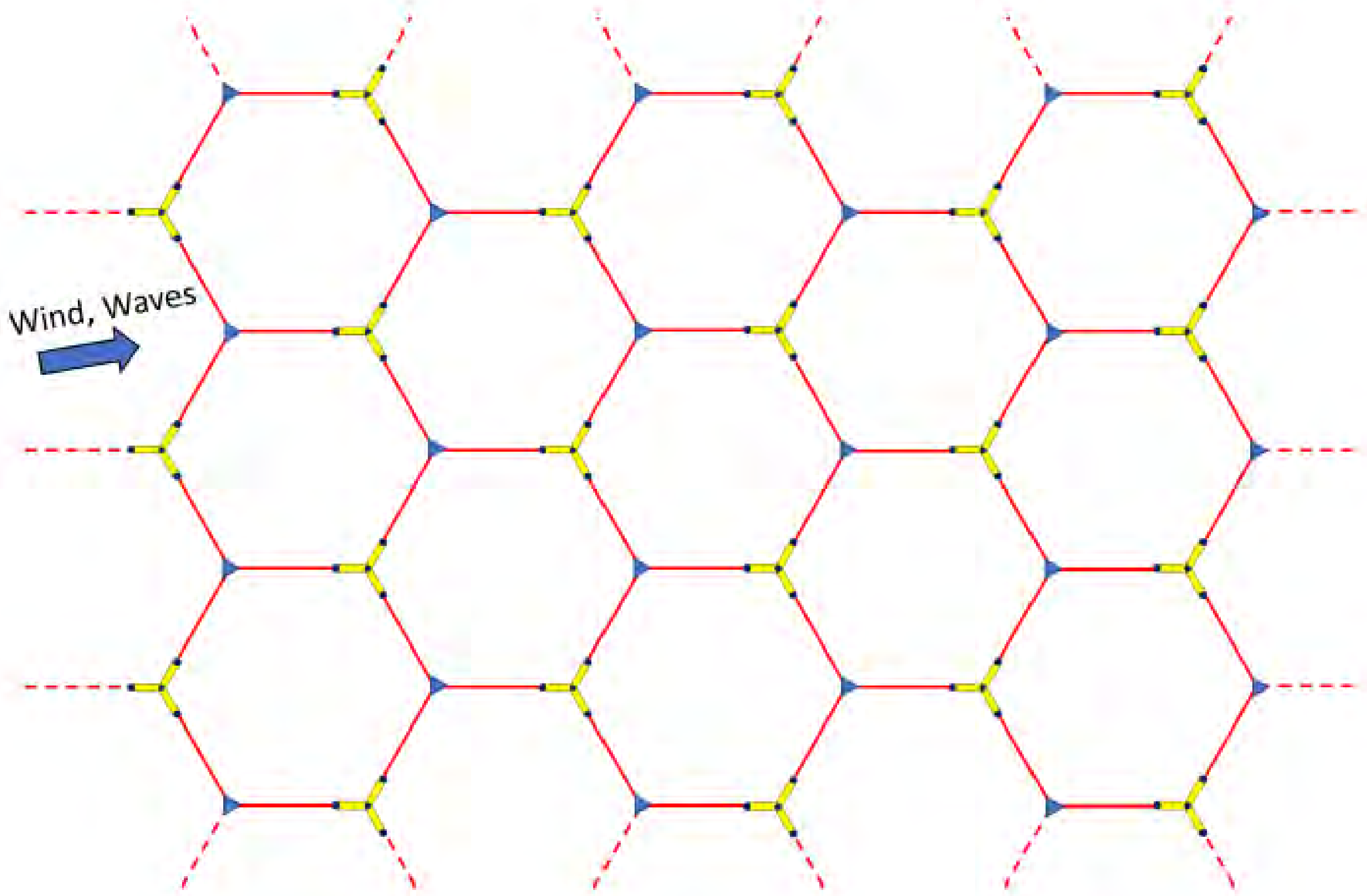




(1) E. Gaertner *et al.*, 'Definition of the IEA Wind 15-Megawatt Offshore Reference wind Turbine', Mar. 2020.
(2) C. Allen *et al.*, 'Definition of the UMaine VolturnUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine', Jul. 2020

Design basis (2/5)





Design basis (3/5)

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Design situation	DLC	Wind Condition	Waves	Wind and wave directionality	Sea currents	Other conditions	Limit state
Power Production	1.6	NTM $V_{in} < V_{hub} < V_{out}$	SSS $H_s = H_{s,SSS}$	COD, UNI	NCM	-	ULS
Parked	6.1	EWM $V_{hub} = V_{50}$	ESS $H_s = H_{s,50}$	MIS, MUL	ECM $U = U_{50}$	Yaw misalignment of ±8 deg Possible yaw slippage	ULS
	6.6 Case 1	EWM $V_{hub} = V_{50}$	ESS $H_s = H_{s,500}$	MIS, MUL	ECM $U = U_5$	Robustness check	ALS
	6.6 Case 2	EWM $V_{hub} = V_{500}$	ESS $H_s = H_{s,50}$	MIS, MUL	ECM $U = U_5$	Robustness check	ALS
Parked + occurrence of fault	7.3	EWM $V_{hub} = V_{50}$	ESS $H_s = H_{s,50}$	MIS, MUL	ECM $U = U_{50}$	Transient condition between intact and redundancy Check condition	ALS
	7.4	EWM $V_{hub} = V_{50}$	ESS $H_s = H_{s,50}$	MIS, MUL	ECM $U = U_{50}$	Redundancy check condition	ALS

Case	Wind	Wave		Current
	V_{hub} [m/s]	H_s [m]	T_p [s]	U_c [m/s]
	DLC 1.6			
1	10.6	6	10	0.5
2	10.6	6	15	0.5
3	10.6	6	20	0.5
4	25	9	12	0.5
5	25	9	16	0.5
6	25	9	20	0.5
	DLC 6.1 / 7.3 / 7.4			
7	40	11	13	1.0
8	40	11	15	1.0
9	40	11	17	1.0
	DLC 6.6			
10	45	11	15	0.8
11	40	13	16	0.8
	DLC 6.1 Cyclonic			
12	57	11.5	15	1.0

Design basis (4/5)

Rules choice: DNV-GL

Limit state	Load factor	Consequence class	
		1	2
ULS	γ_{mean}	1.3	1.5
ULS	γ_{dyn}	1.75	2.2
ALS	γ_{mean}	1.0	1.0
ALS	γ_{dyn}	1.1	1.25

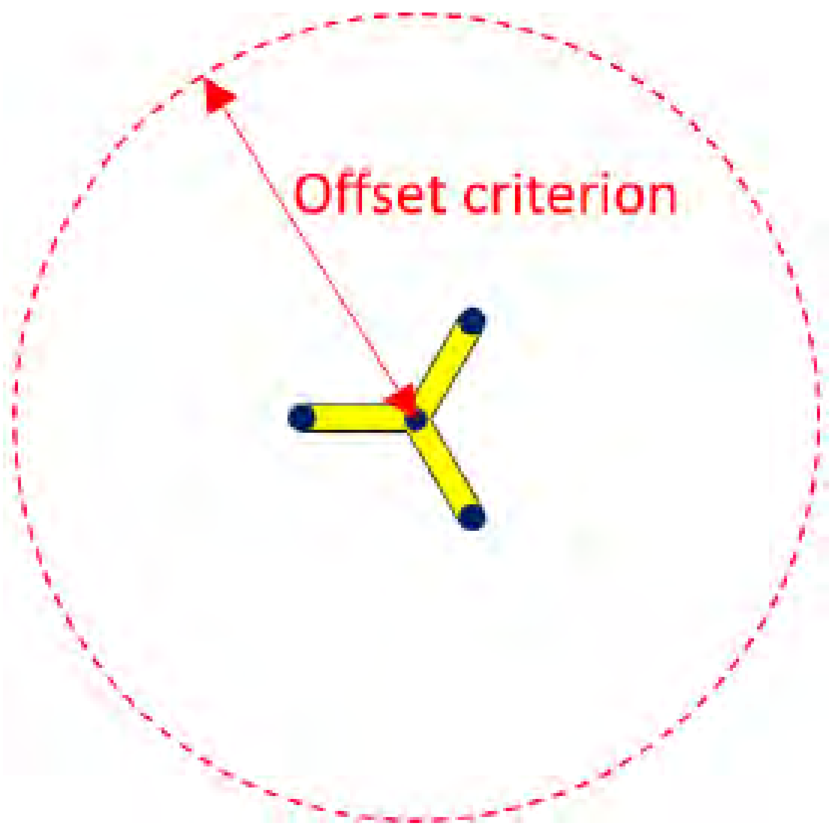
$$T_d = \gamma_{mean} * T_{c,mean} + \gamma_{dyn} * T_{c,dyn}$$

$$Td < 0.95 * MBL \leftrightarrow UR < 1$$

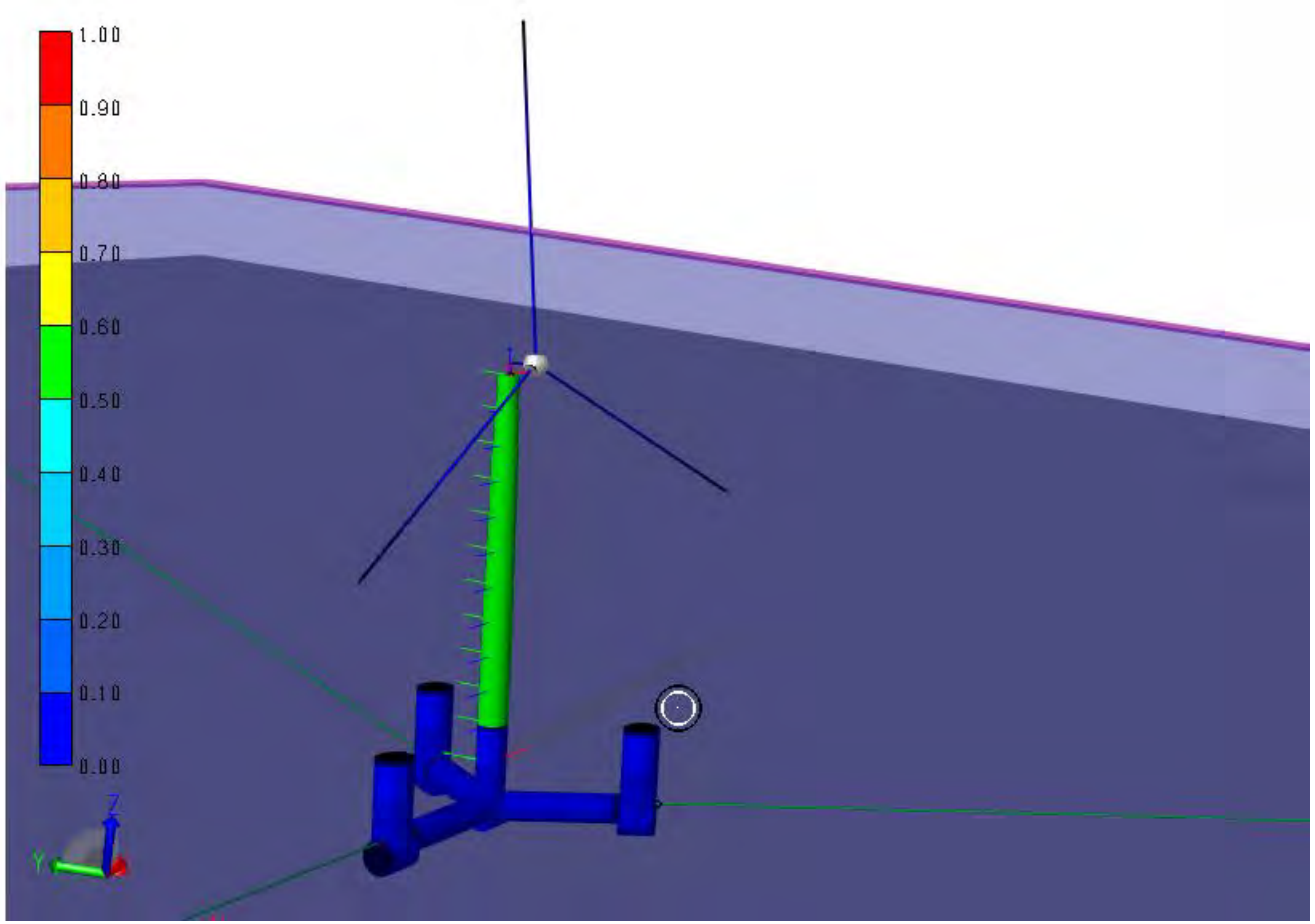
$$with \quad UR = \frac{T_d}{0.95 * MBL}$$

Offset:

Water depth	Offset criteria
80 m	35 m
200 m	50 m
600 m	60 m



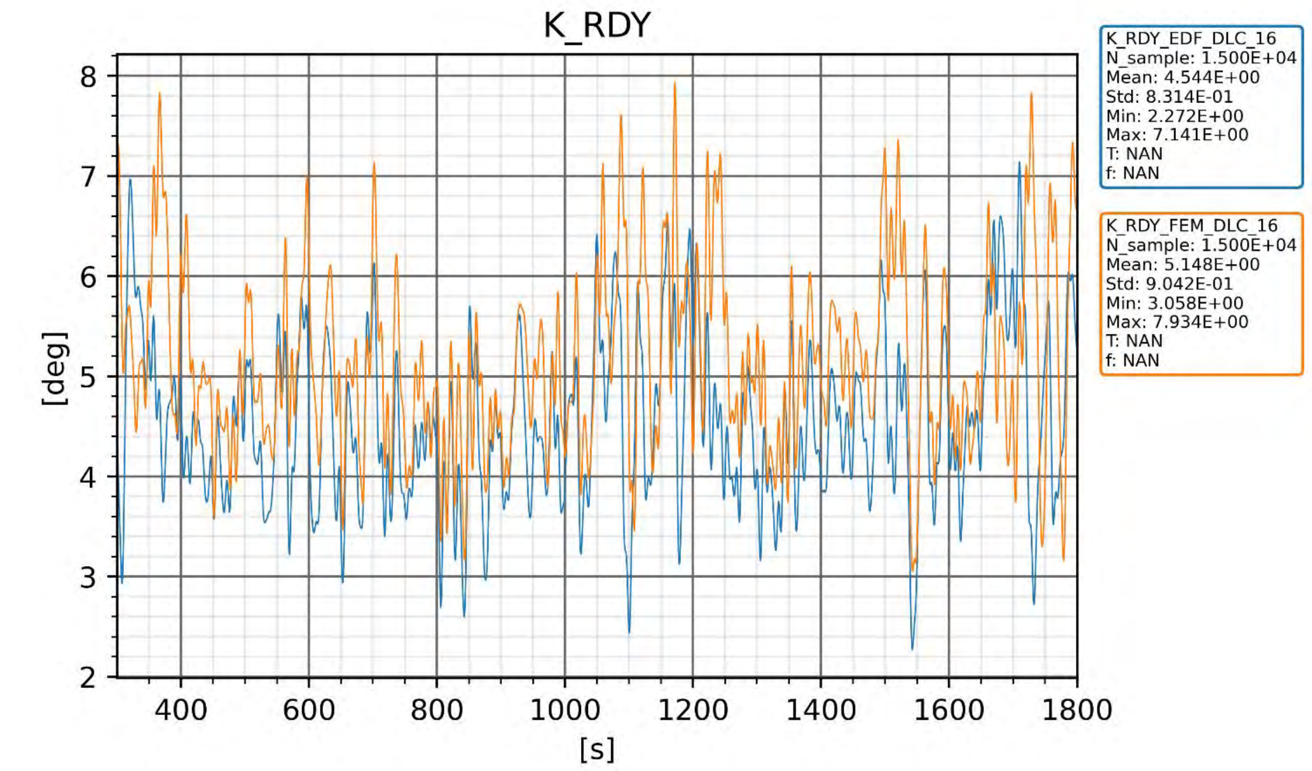
Design basis (5/5)

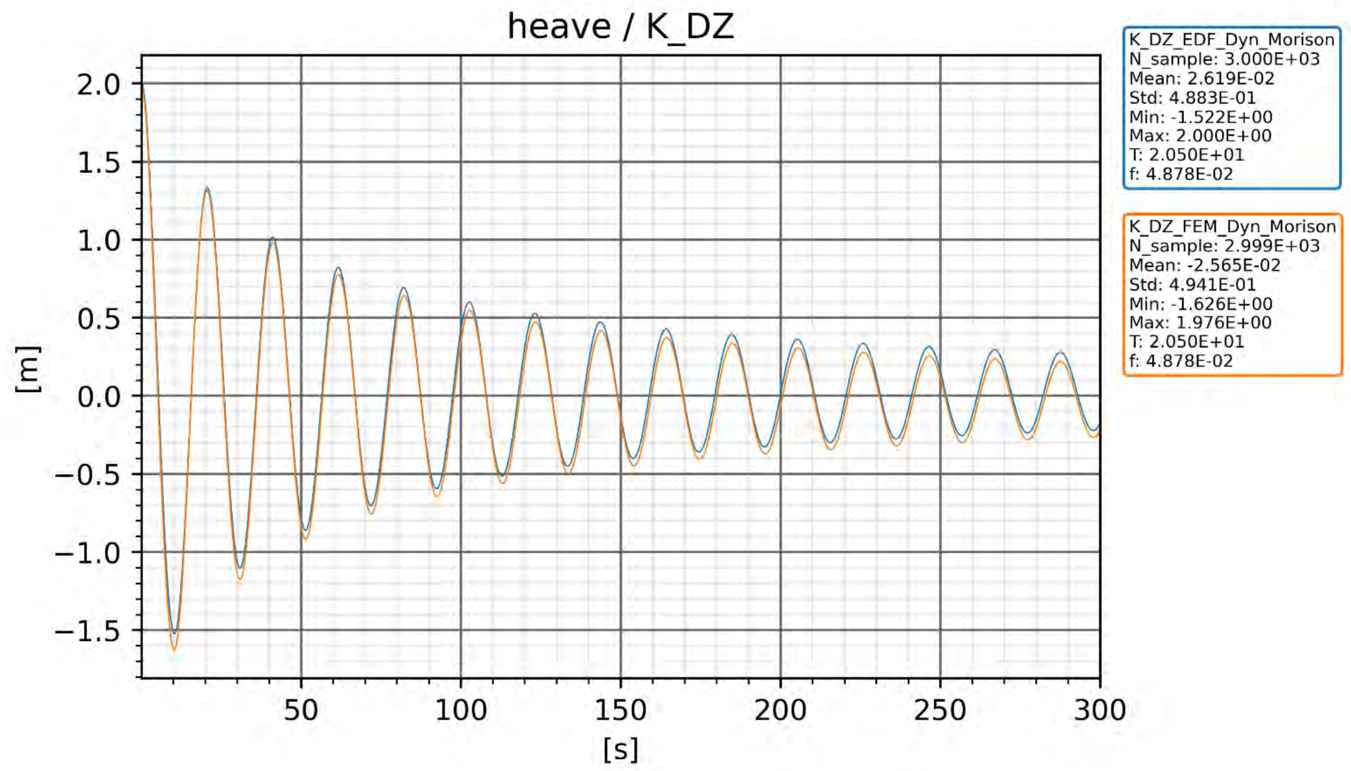


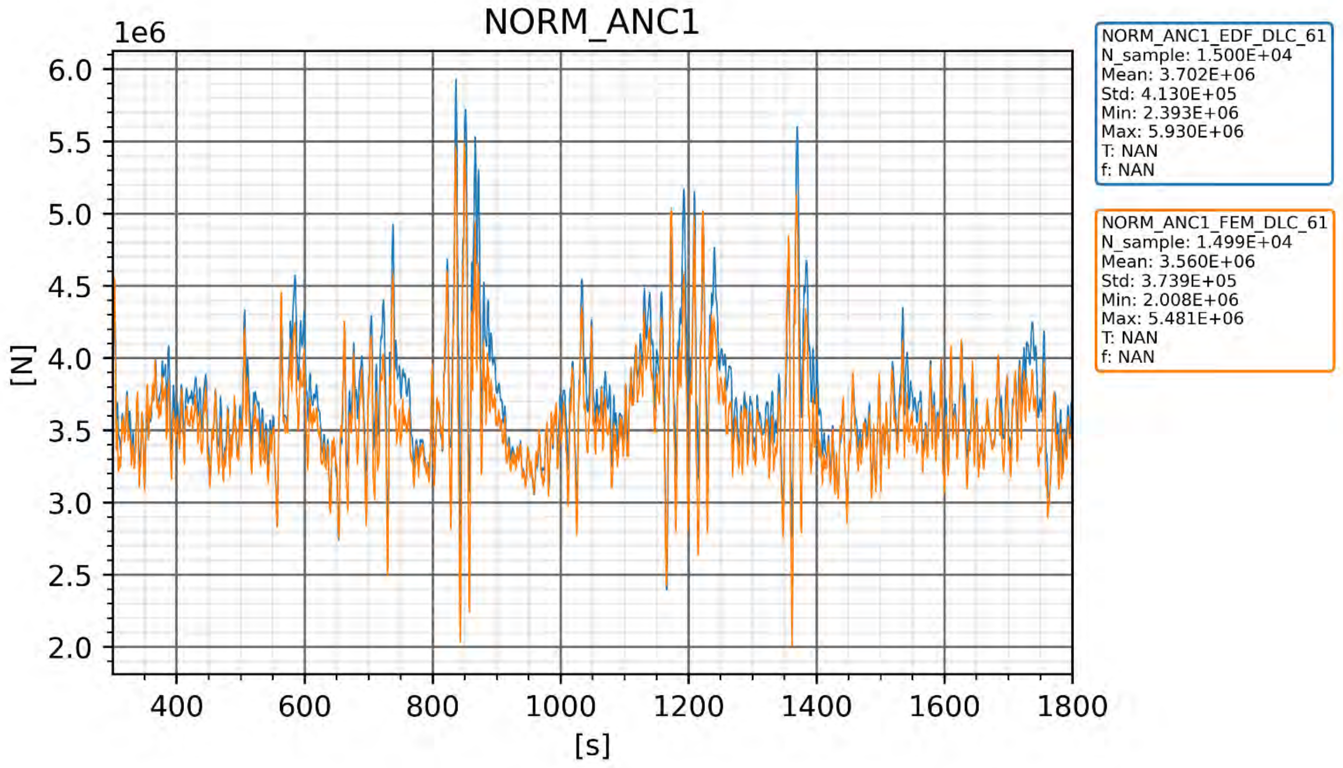
Model

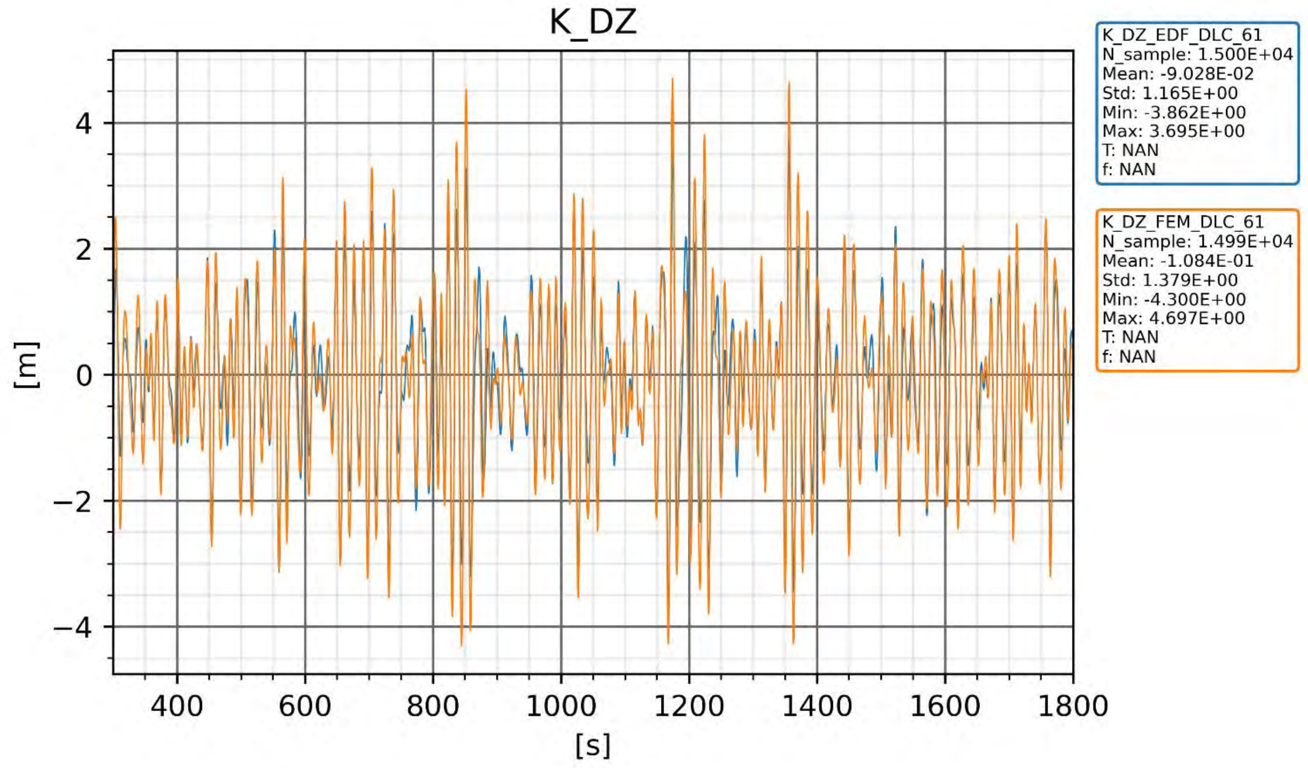
- General:
  - Logiciel: SIMA, Diego
  - Model type: aero-hydro-servo-elastic coupled
- Structure:
  - Blade: rigid
  - Tower: rigid
  - Lines: FEA
  - Anchors: fixed points
- Aero:
  - Turbine: intern control (SIMO), extern (.dll)
  - Blade: BEM method
  - Tower: quadratic drag
- Hydro:
  - Floater: HDB + Morison drag + Mean drift forces
  - Lines: Morison

Mooring design analysis - Benchmark

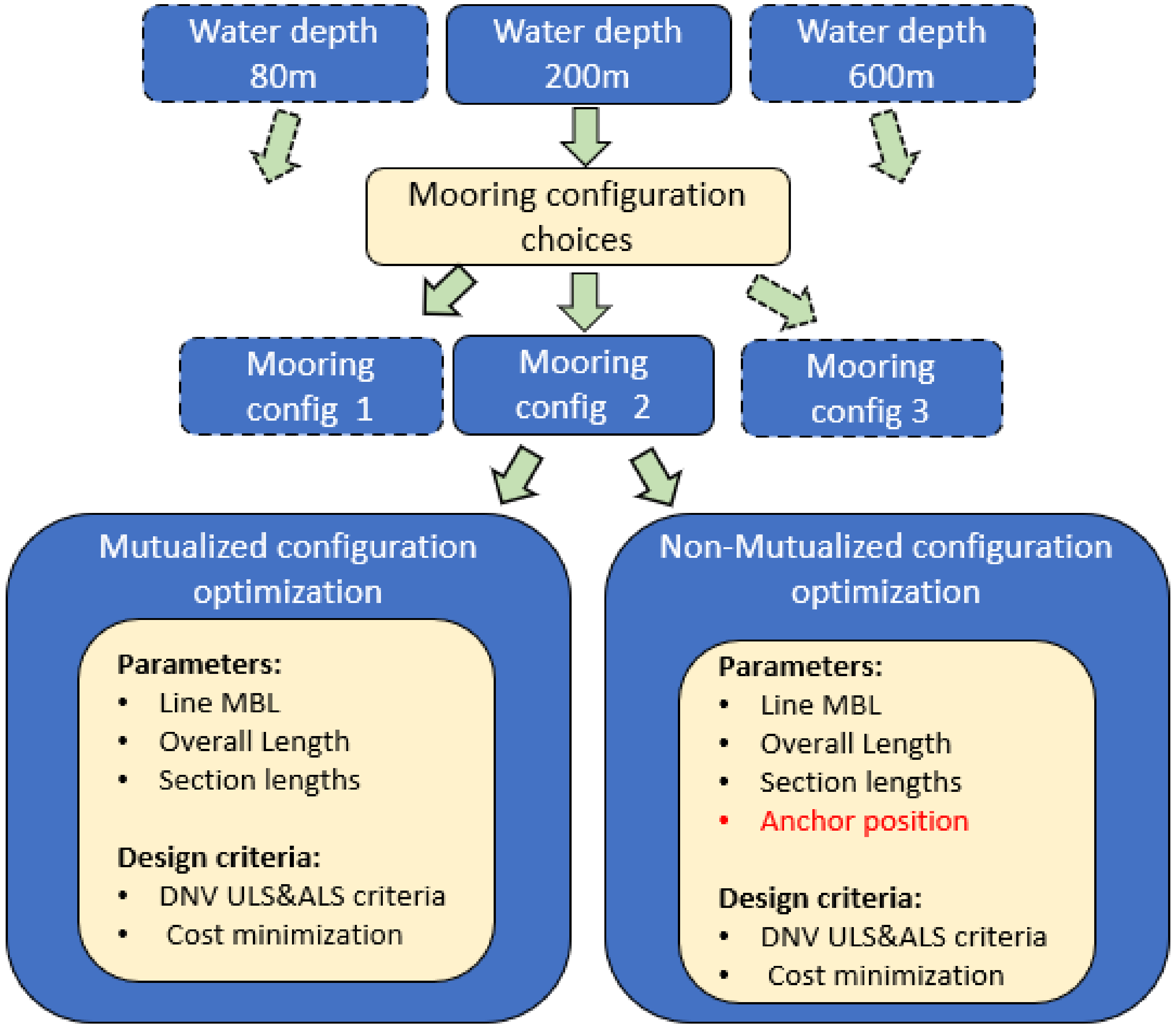


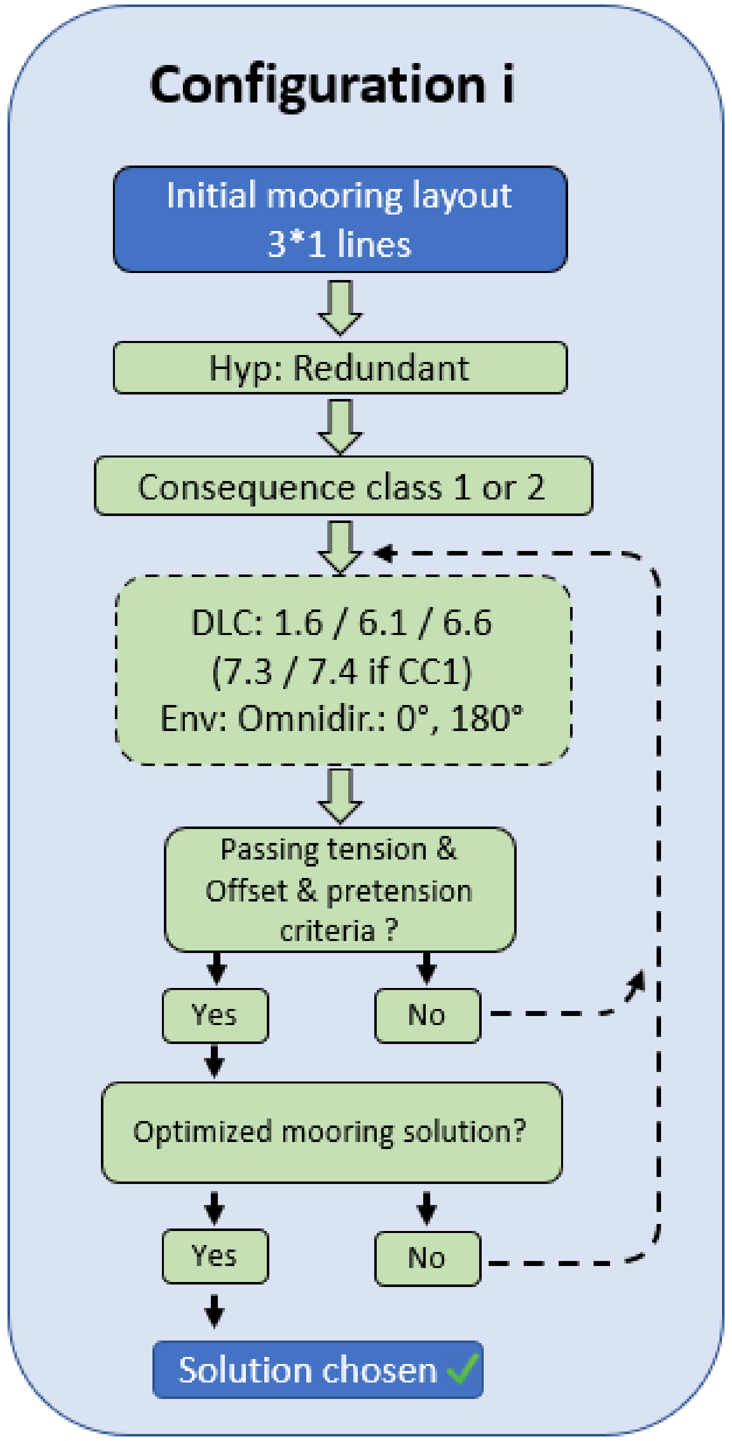






Mooring design analysis – Methodology (1/2)





Mooring design analysis – Methodology (2/2)

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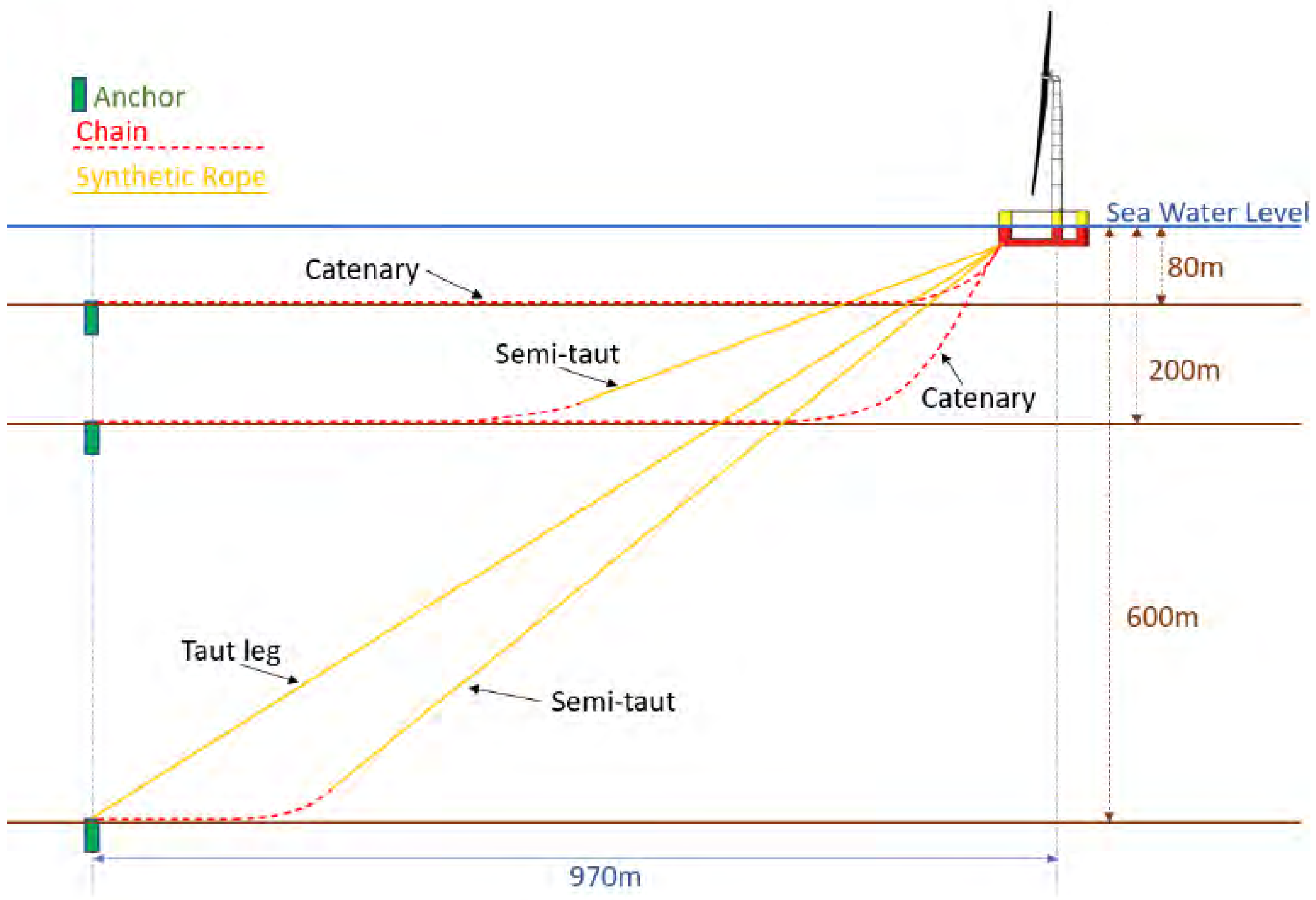
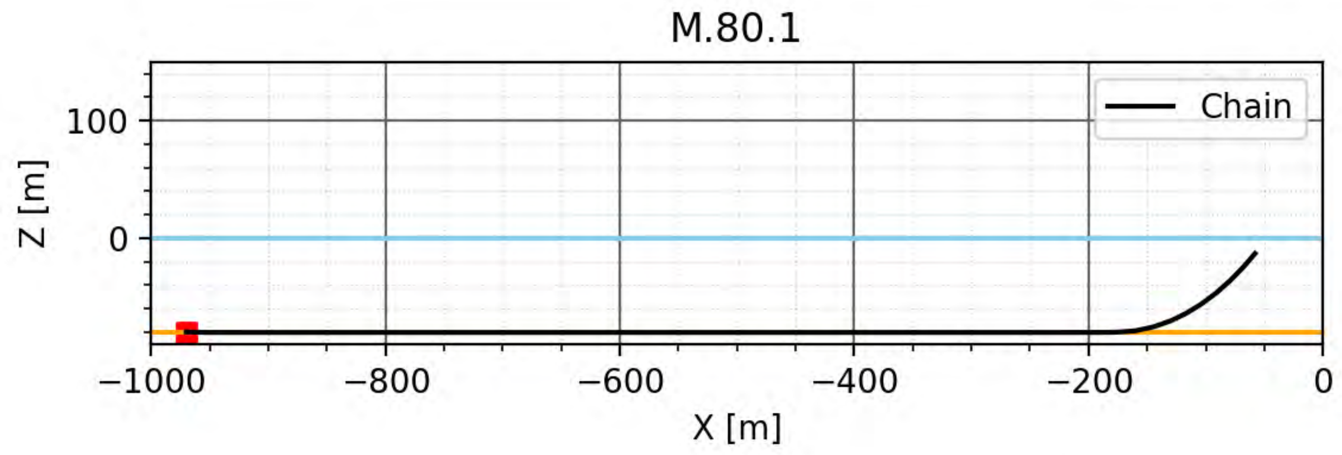
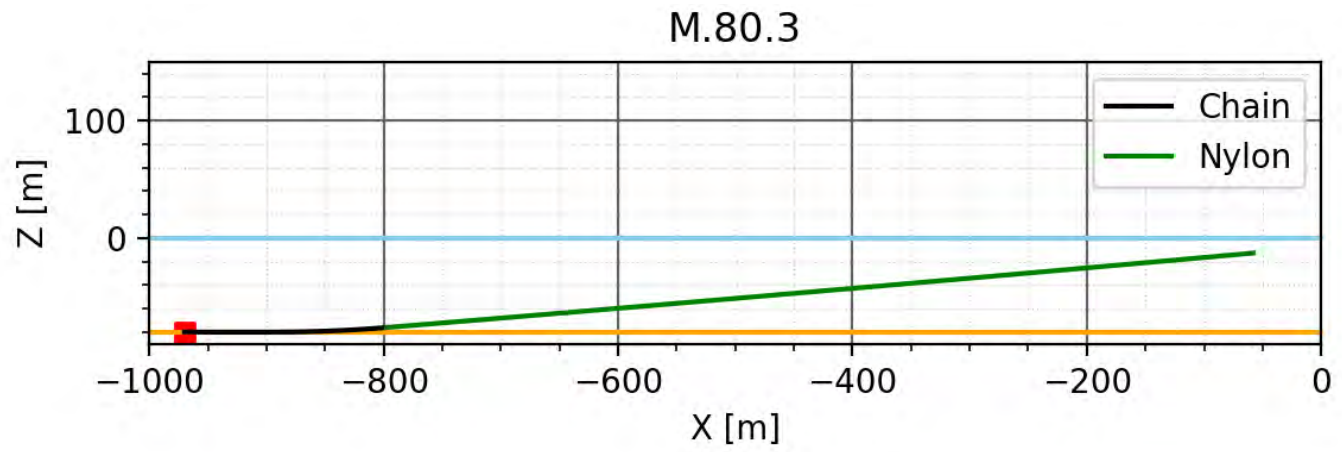


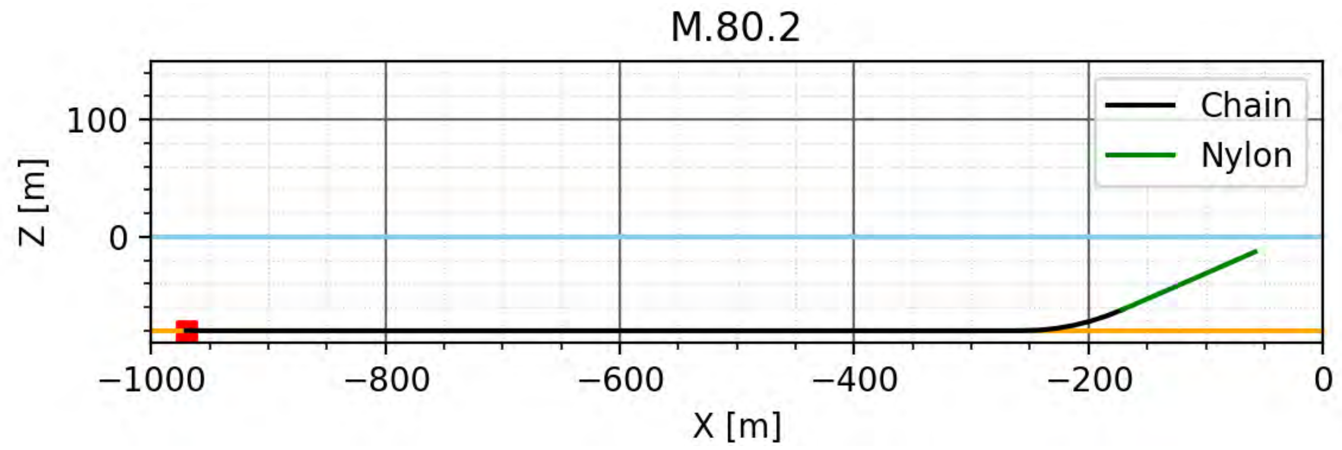
	80m - FEM	200m - EDF	600m - FEM
Configuration 1	100 % Chain	100 % Chain	Polyester
Configuration 2	Chain + Nylon	Chain + Polyester	Chain + Polyester
Configuration 3	Chain + HMPE	Chain + HMPE	Chain + HMPE

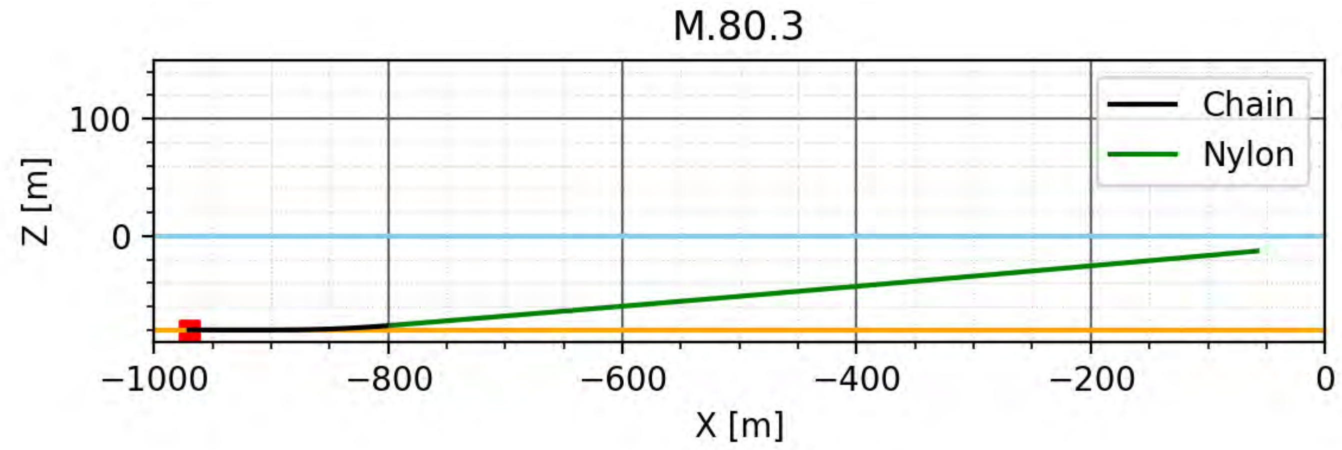
Mooring design analysis - 80m water depth (1/2)

	Configuration index	Type	CC	Anchor radius [m]	MBL [kN]	Mooring length [m]	Pre-tension [kN]
Water Depth 80 m	M.80.1 (= NM.80.1)	Chain	1	970			
	M.80.2 (= NM.80.2)	Chain/Nylon	1	970			
	M.80.3	Chain/Nylon	1	970			
	NM.80.3	Chain/Nylon	1	658			



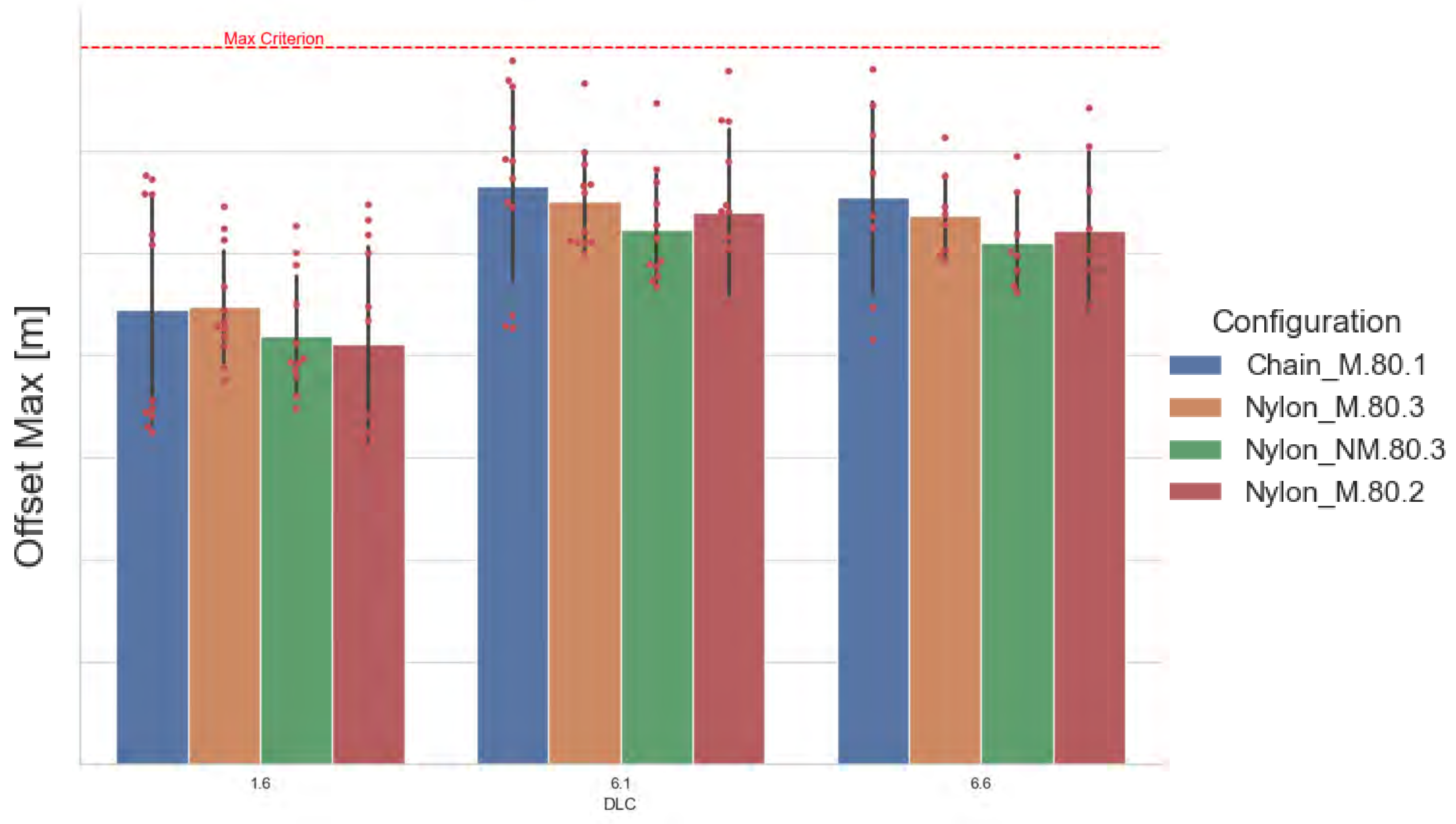


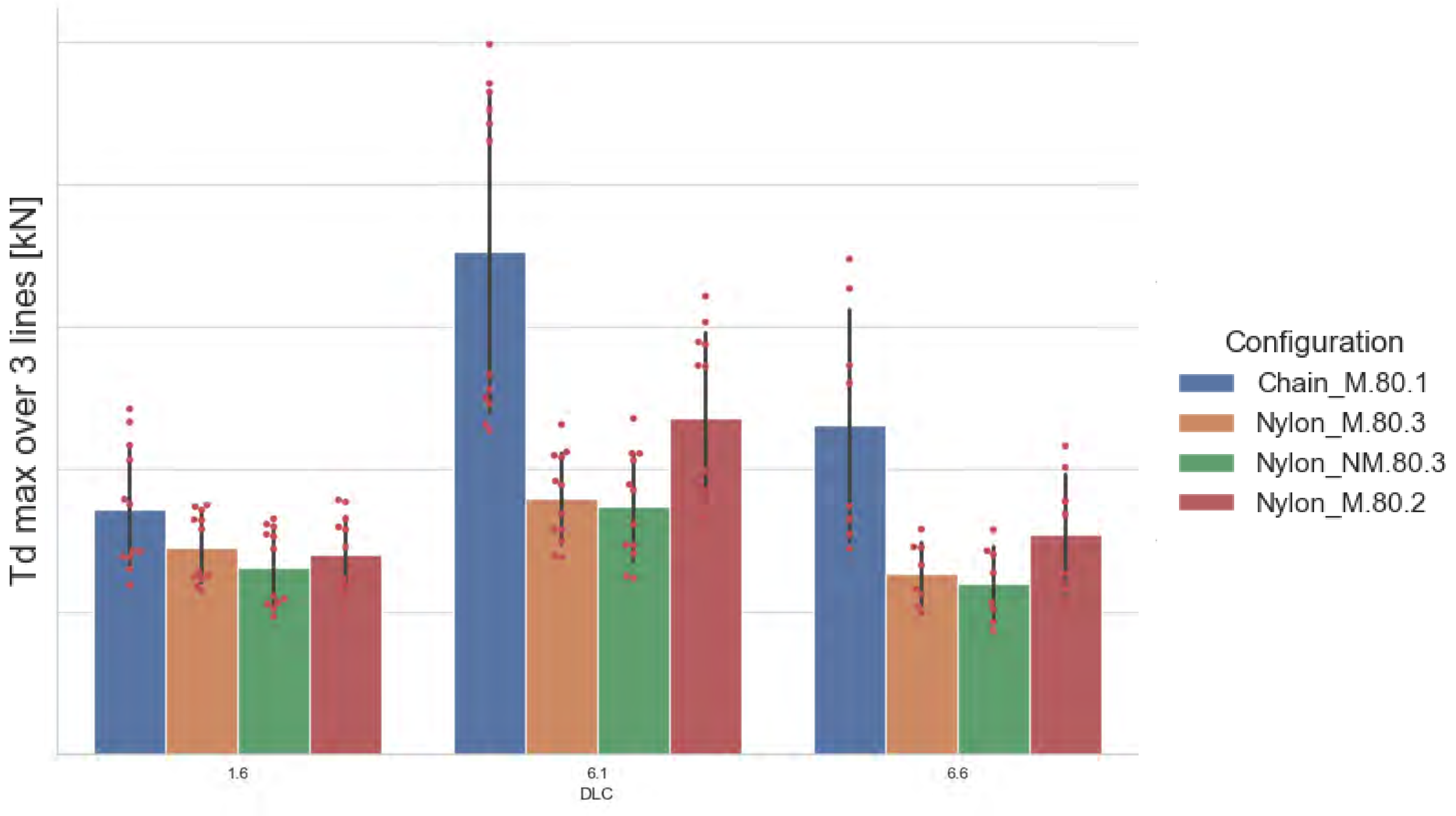




Mooring design analysis - 80m water depth (2/2)

	Configuration index	Type	CC	Anchor radius [m]	MBL [kN]	Mooring length [m]	Pre-tension [kN]	Design tension [kN]	Utilization Ratio [kN]	Offset max[m]
Water Depth 80 m	M.80.1 (= NM.80.1)	Chain	1	970					0.99	34
	M.80.2 (= NM.80.2)	Chain/Nylon	1	970					0.96	34
	M.80.3	Chain/Nylon	1	970					0.93	33
	NM.80.3	Chain/Nylon	1	658					0.92	32





Mooring design analysis - 600m water depth

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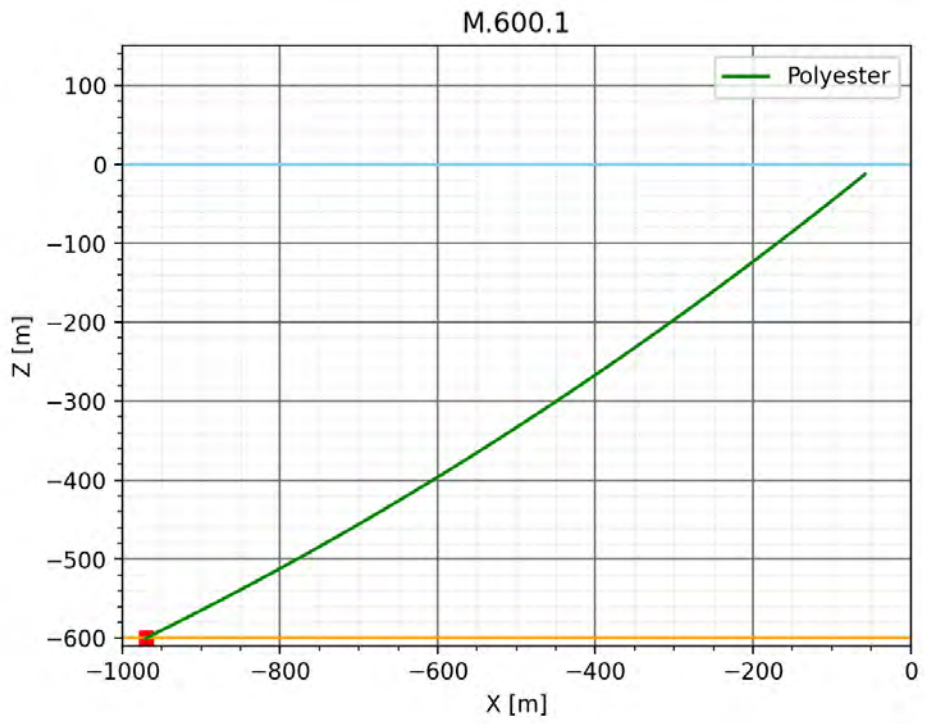
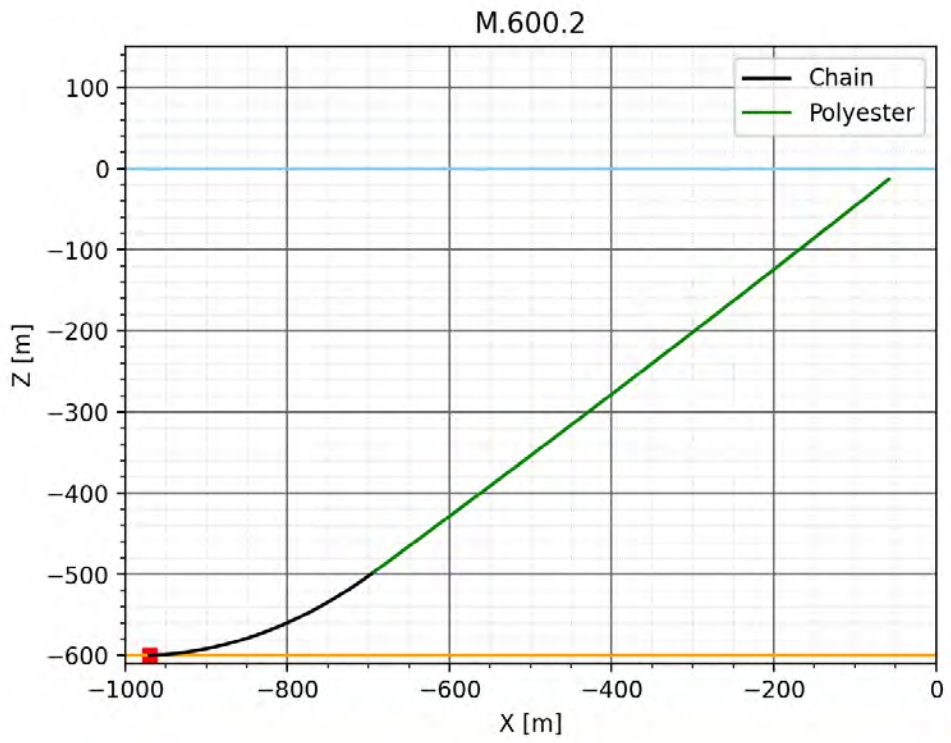
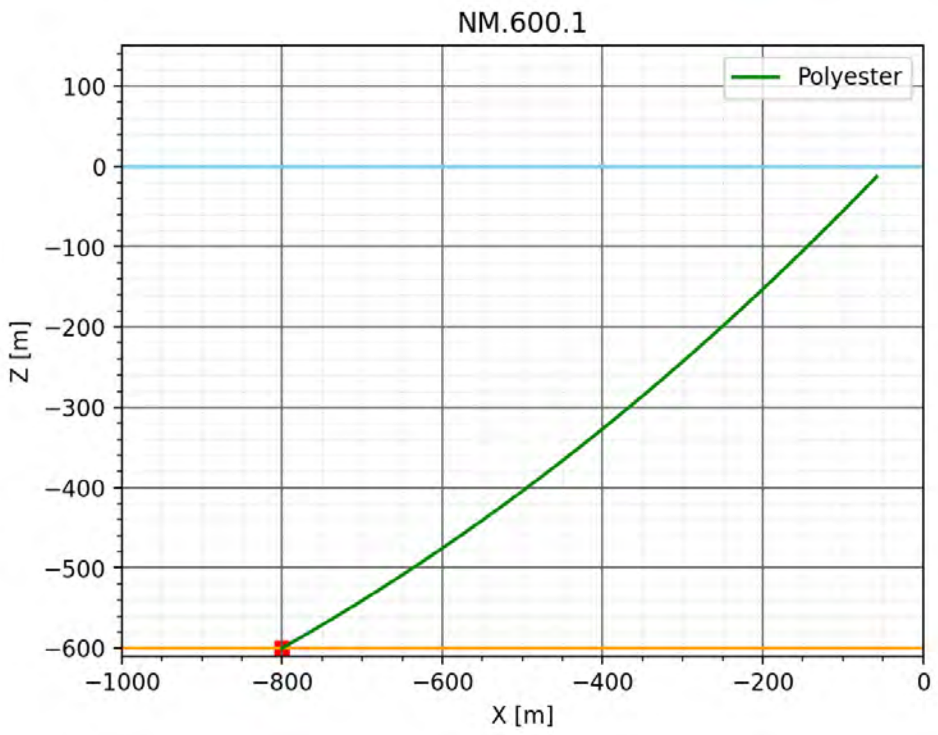
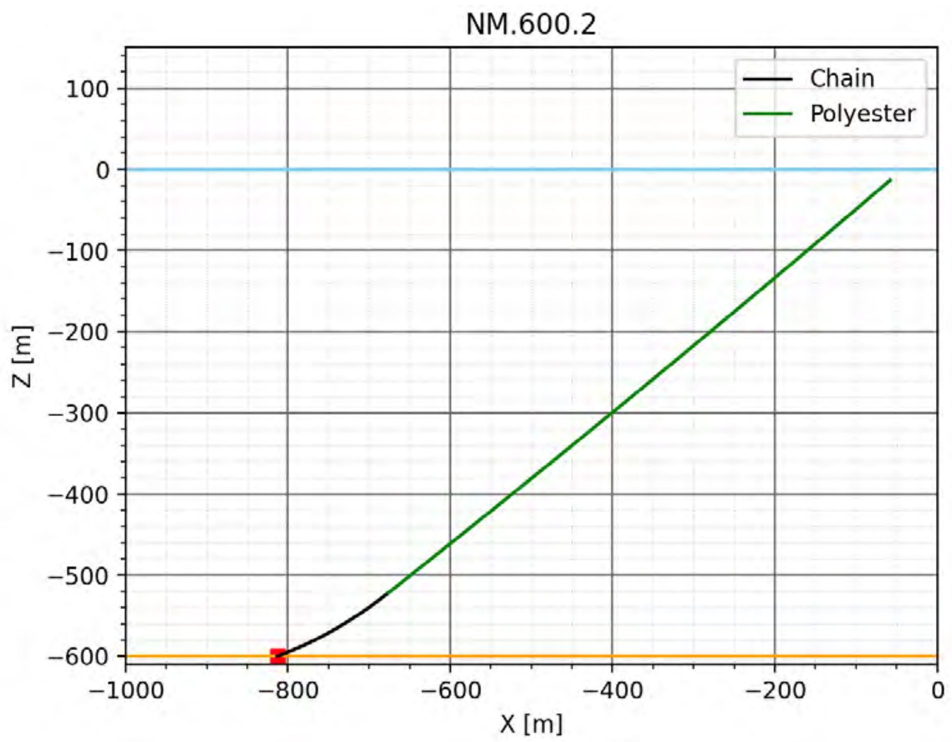
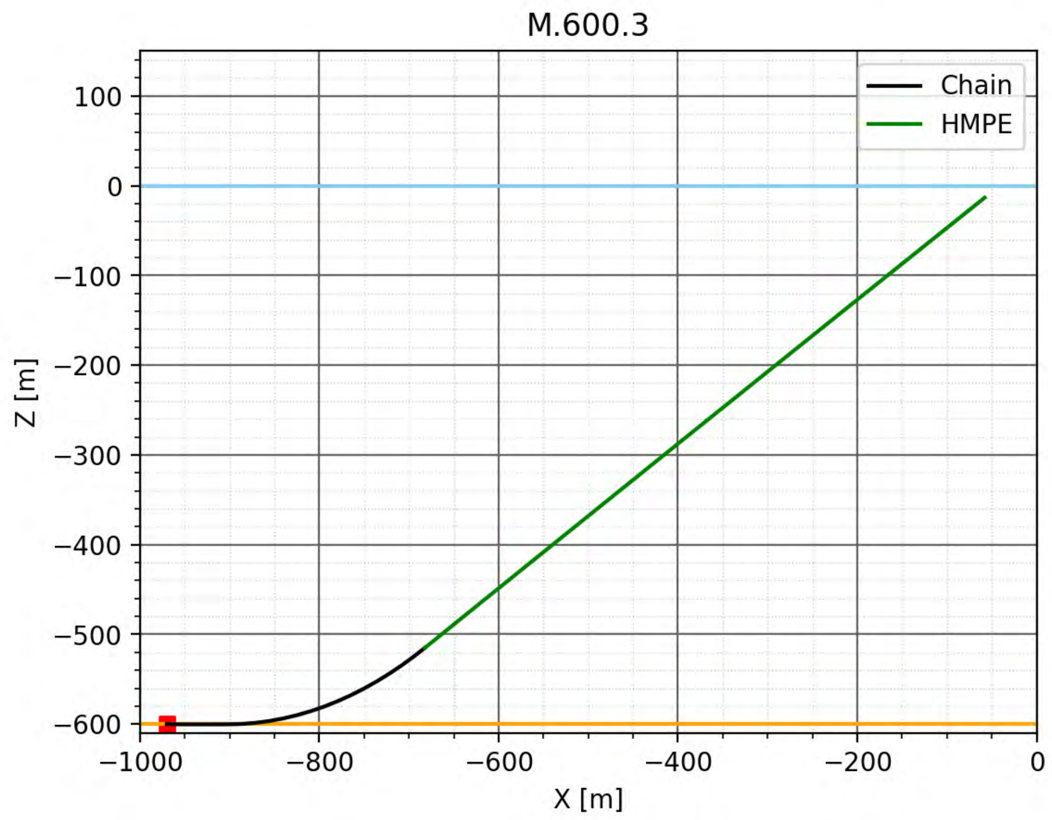




	Configuration index	Type	CC	Anchor radius [m]	MBL [kN]	Mooring length [m]	Pre-tension [kN]
Water Depth 600 m	M.600.1	Polyester	1	970			
	NM.600.1	Polyester	1	800			
	M.600.2	Chain/Polyester	1	970			
	NM.600.2	Chain/Polyester	1	813			
	M.600.3 (= NM.600.3)	Chain/HMPE	1	970			

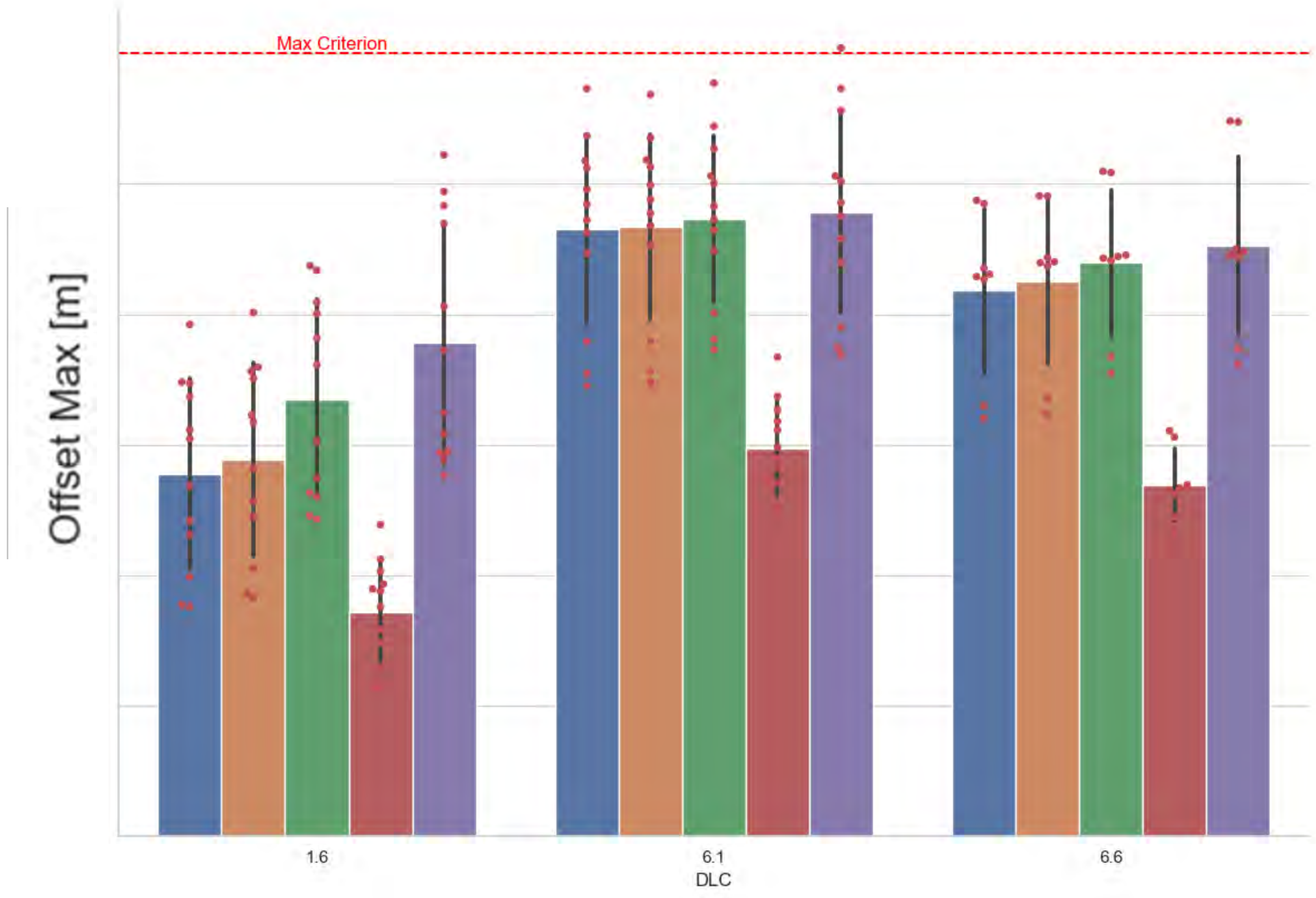


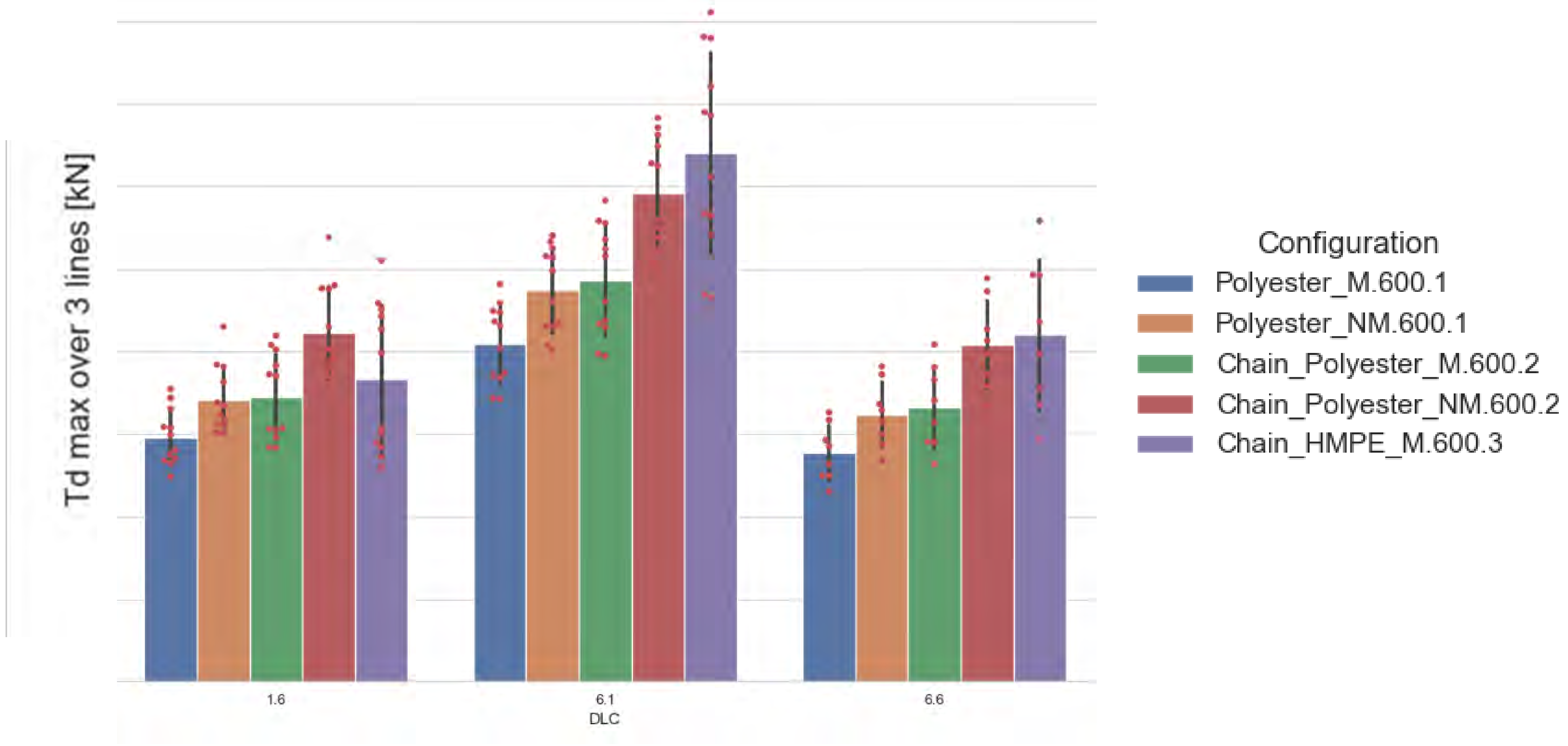




Mooring design analysis (1/3)

	Configuration index	Type	CC	Anchor radius [m]	MBL [kN]	Mooring length [m]	Pre-tension [kN]	Design tension [kN]	Utilization Ratio [kN]	Offset max[m]
Water Depth 600 m	M.600.1	Polyester	1	970					0.97	57
	NM.600.1	Polyester	1	800					0.98	57
	M.600.2	Chain/Polyester	1	970					0.98	58
	NM.600.2	Chain/Polyester	1	813					0.99	37
	M.600.3 (= NM.600.3)	Chain/HMPE	1	970					0.97	60





Mooring design analysis (2/3)

	Configuration index	Type	CC	Anchor radius [m]	MBL [kN]	Mooring length [m]	Pre-tension [kN]	Design tension [kN]	Utilization Ratio [kN]	Offset max[m]	Single line Cost [k€]
Water Depth 80 m	M.80.1 (= NM.80.1)	Chain	1	970.00					0.99	34.40	
	M.80.2 (= NM.80.2)	Chain/Nylon	1	970.00					0.96	33.90	
	M.80.3	Chain/Nylon	1	970.00					0.93	33.30	
	NM.80.3	Chain/Nylon	1	658.00					0.92	32.30	
Water Depth 600 m	M.600.1	Polyester	1	970.00					0.97	57.30	
	NM.600.1	Polyester	1	800.00					0.98	56.90	
	M.600.2	Chain/Polyester	1	970.00					0.98	57.70	
	NM.600.2	Chain/Polyester	1	813.00					0.99	36.70	
	M.600.3 (= NM.600.3)	Chain/HMPE	1	970.00					0.97	60.40	

Various type of configurations were studied

- Chain, Nylon, Polyester, HMPE
- Horizontal loadings, Hybrid loadings
- Water depth: 80m, 200m, 600m

Environmental conditions were pushing the design to manufacturable limits

- Several cases did not allow optimization for non shared cases
- Line cluster could have been an option but complicated to evaluate in the frame of the MUTANC project

Mooring design analysis (3/3)

	Configuration index	Type	Pre-tension [kN]	MBL [kN]	Chain Length [m]	HMPE Length [m]	Nylon Length [m]	Polyester Length [m]	Total Length [m]	Single line Cost [k€]
Water Depth 80 m	M.80.1 (= NM.80.1)	Chain								
	M.80.2 (= NM.80.2)	Chain/Nylon								
	M.80.3	Chain/Nylon								
	NM.80.3	Chain/Nylon								
Water Depth 600 m	M.600.1	Polyester								
	NM.600.1	Polyester								
	M.600.2	Chain/Polyester								
	NM.600.2	Chain/Polyester								
	M.600.3 (= NM.600.3)	Chain/HMPE								

Cost including:

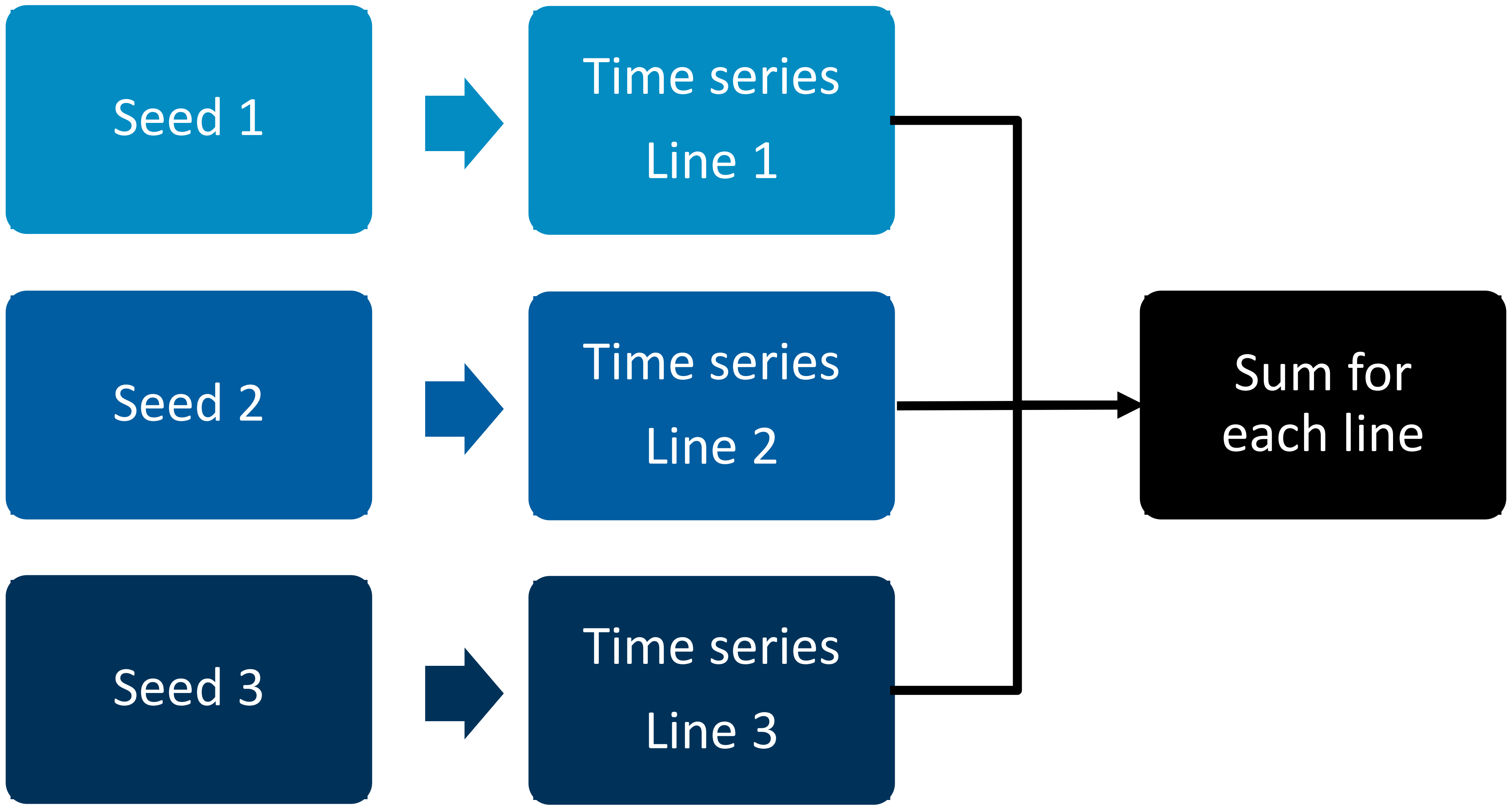
- Material cost
- Intra line connectors cost
- End line connectors cost
- Tensioner cost (1 every 3 lines)

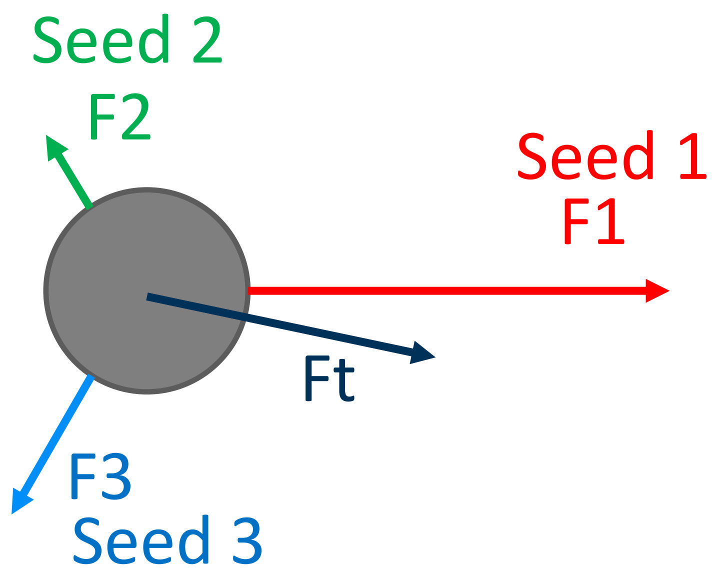
Cost does not include anchor cost and installation cost

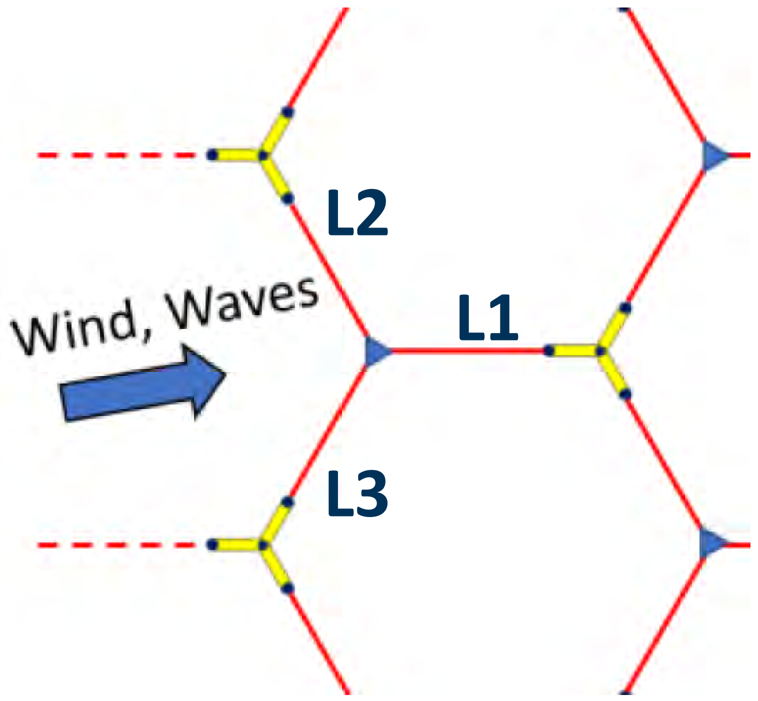
Observations

- **Synthetic fibers** provide a significant cost saving, in particular with Nylon 80m and Polyester 600m
- **Fatigue analysis** were not conducted (would be necessary to conclude with the previous point)
- **Industrial knowledge** about long term behavior for Nylon is missing
  - This is currently investigated in the BAMOS JIP

Mooring loads at anchor - Hypothesis



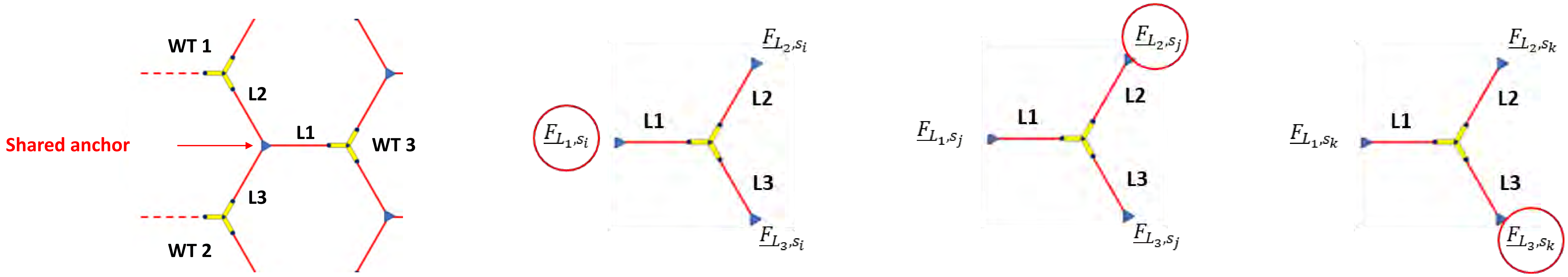




Hypothesis

- **Wind** is not correlated between two turbines
- **Waves** are not correlated between two turbines

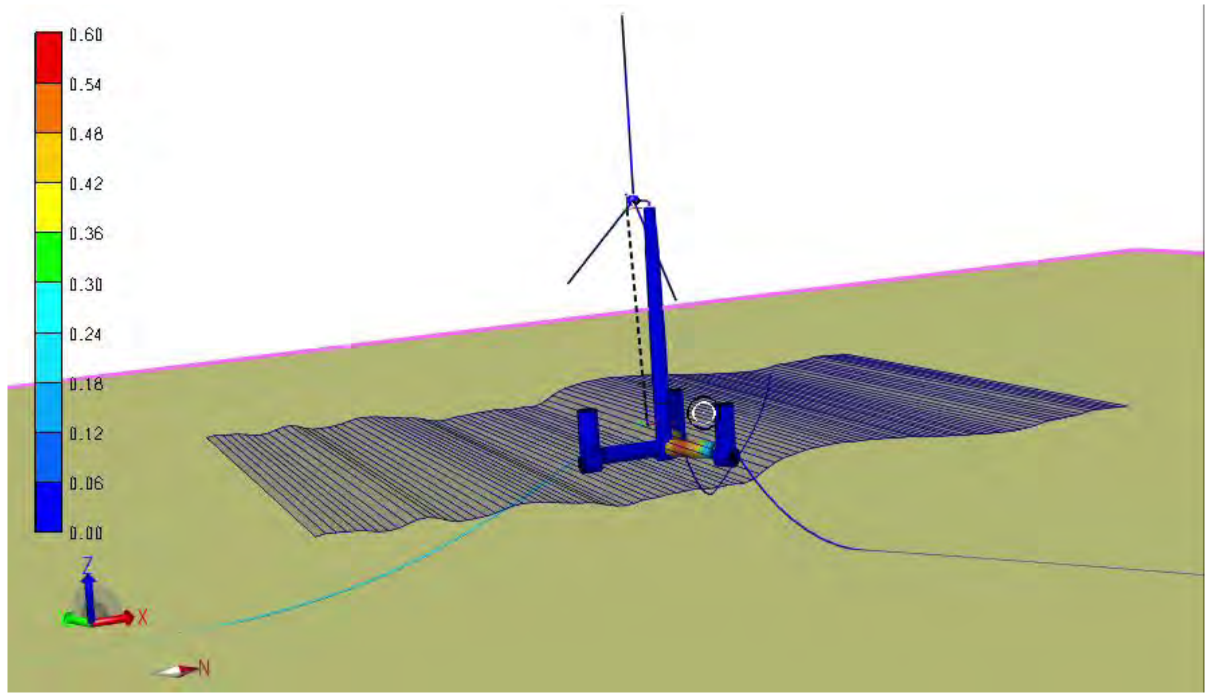
Mooring loads at anchor - Combinations



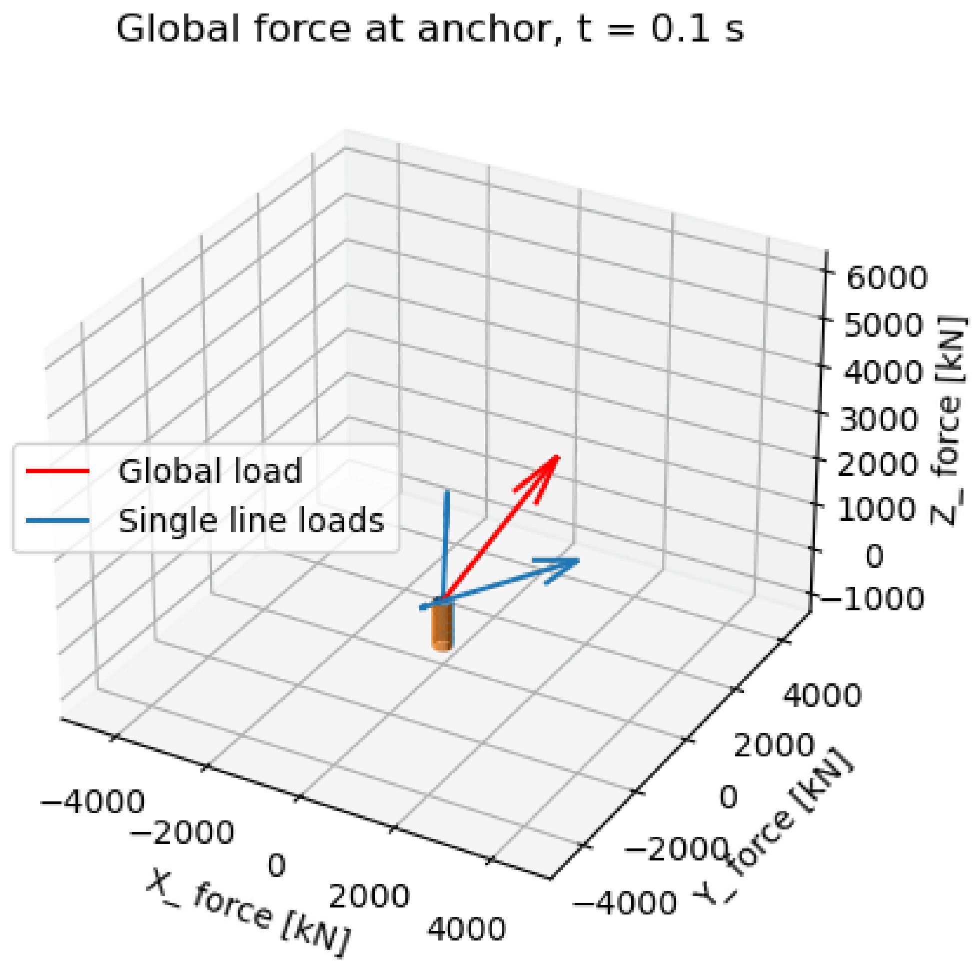
$$\underline{F}_{\text{mutualized}} = \underline{F}_{L_1,s_i} + \underline{F}_{L_2,s_j} + \underline{F}_{L_3,s_k}$$

- 120 possible combinations
- The combination with the maximum force the closest to the mean of maximum force is chosen

Mooring loads at anchor - Modelling view

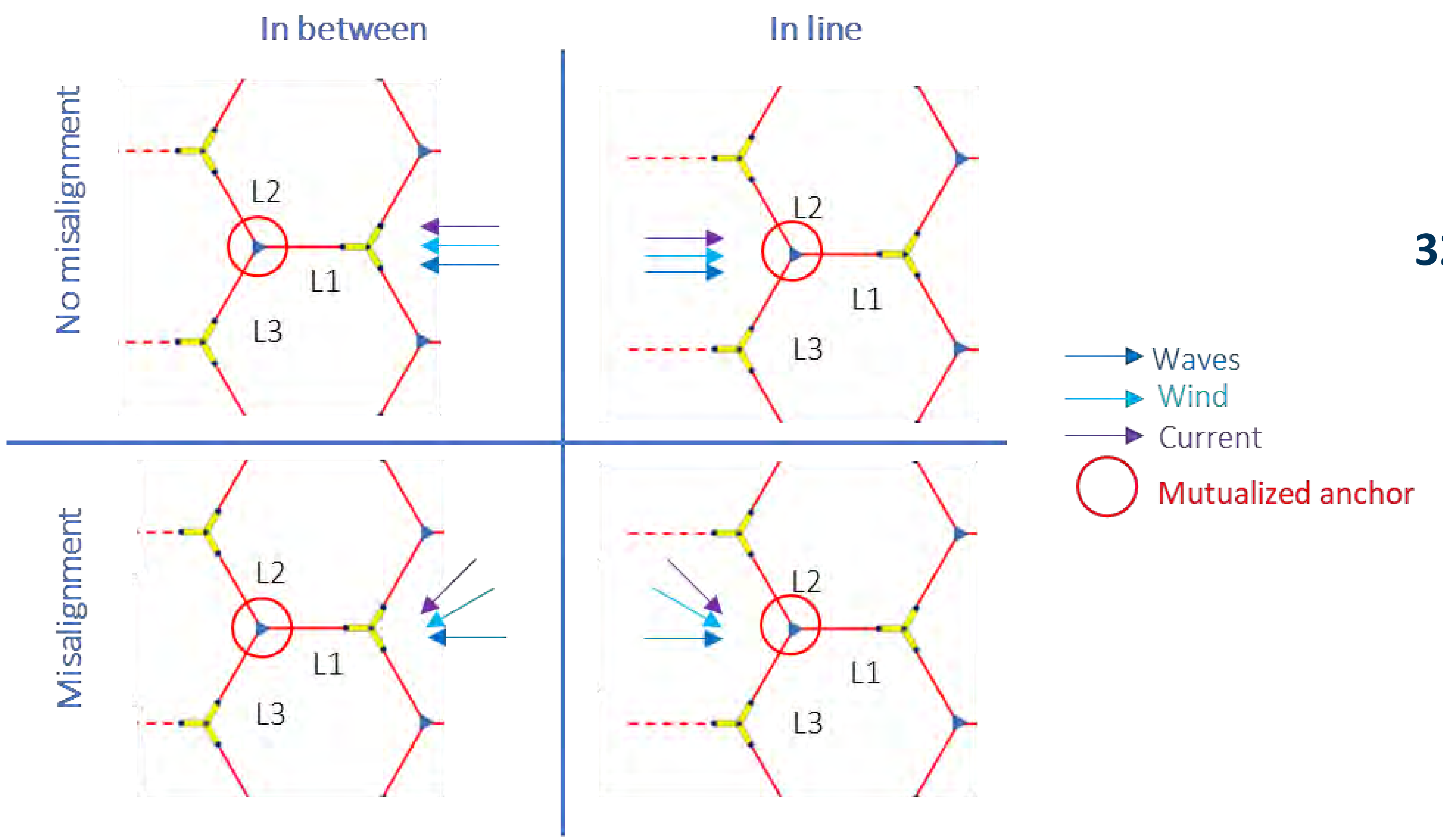


3 different seeds



Water depth: 600 m
Line type: Taut Polyester
Environment: DLC 6.1

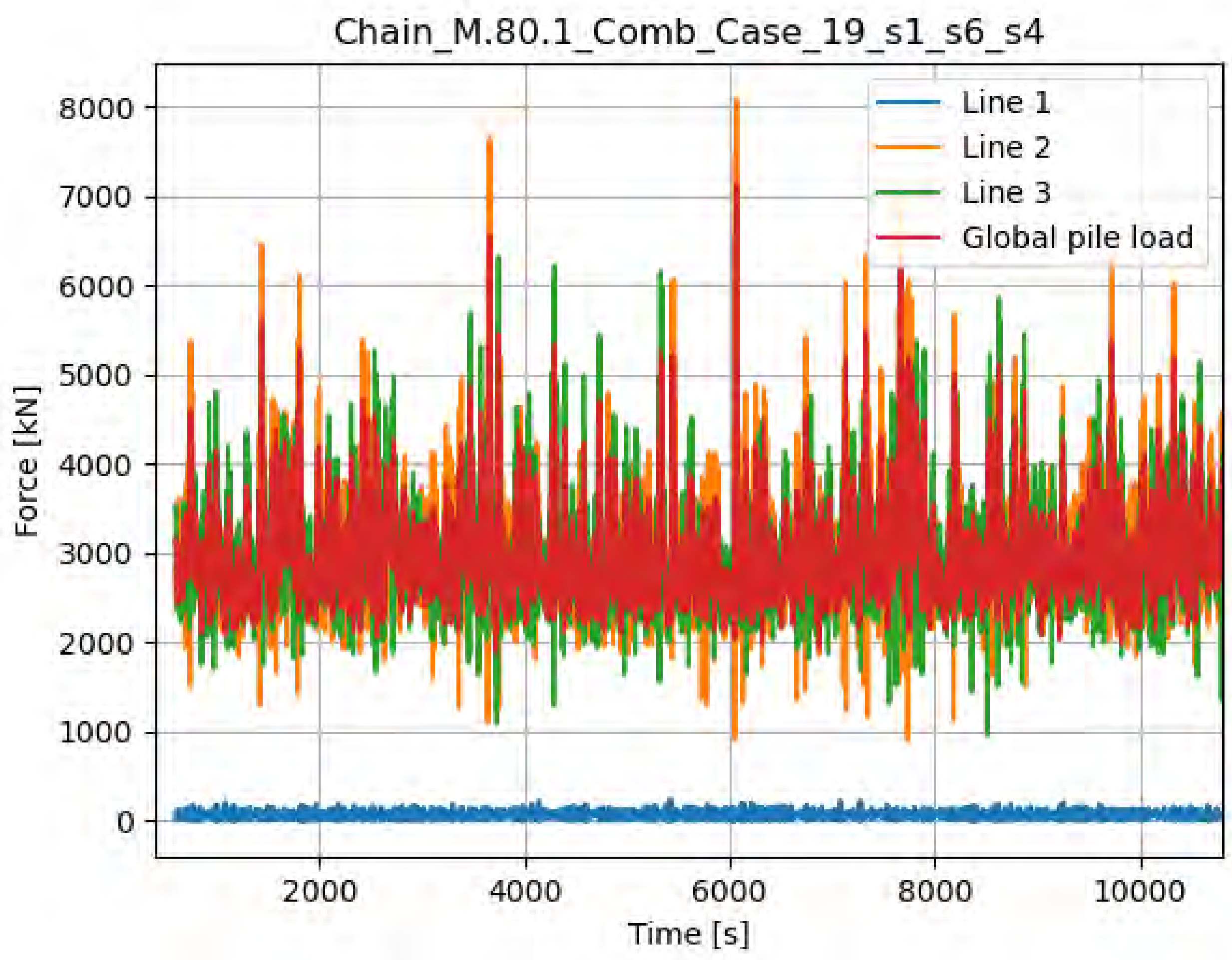
Mooring loads at anchor

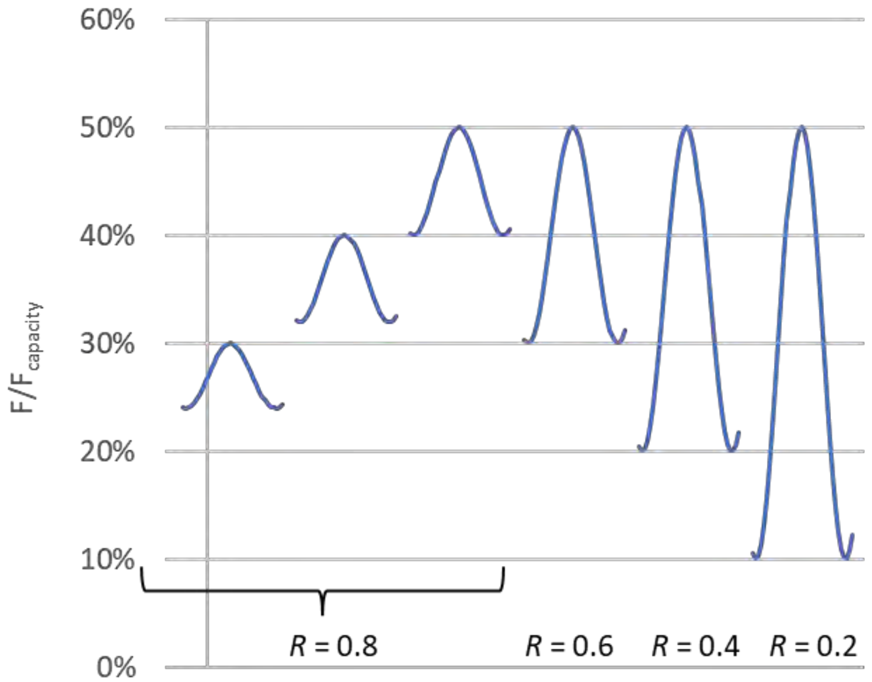


32 cases (*6 seeds) were simulated overall and for each configuration

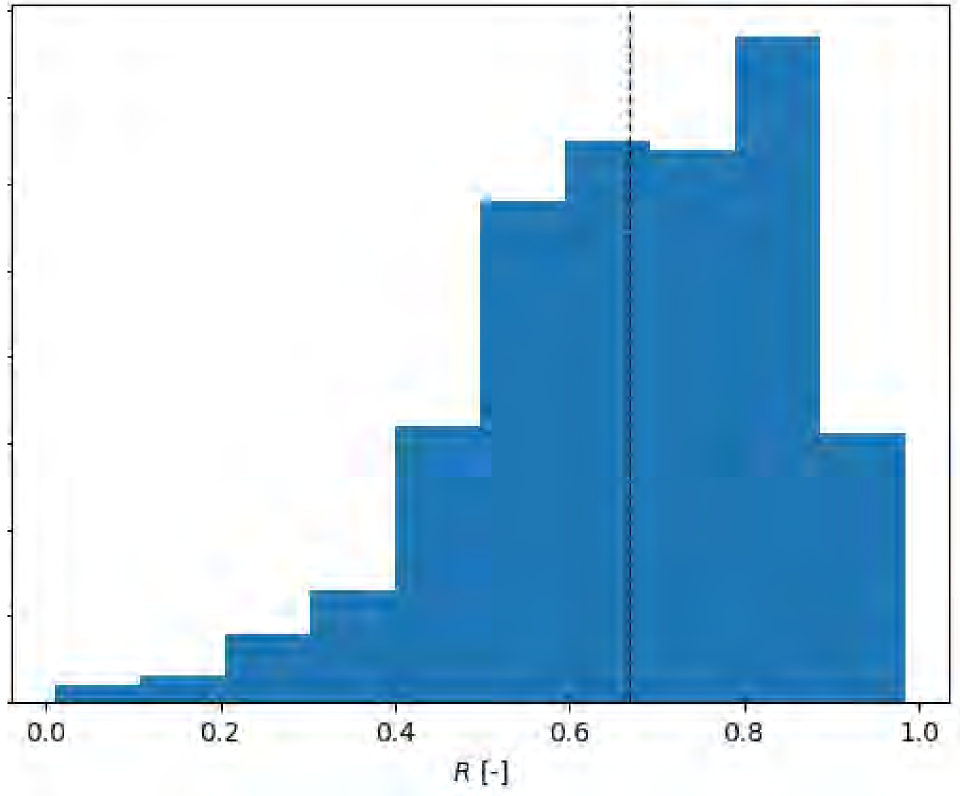
	In line No misalignment	In line Misalignment	In between No misalignment	In between Misalignment
DLC 1.6	6	0	6	-
DLC 6.1	3	3	3	3
DLC 6.6	2	2	2	2

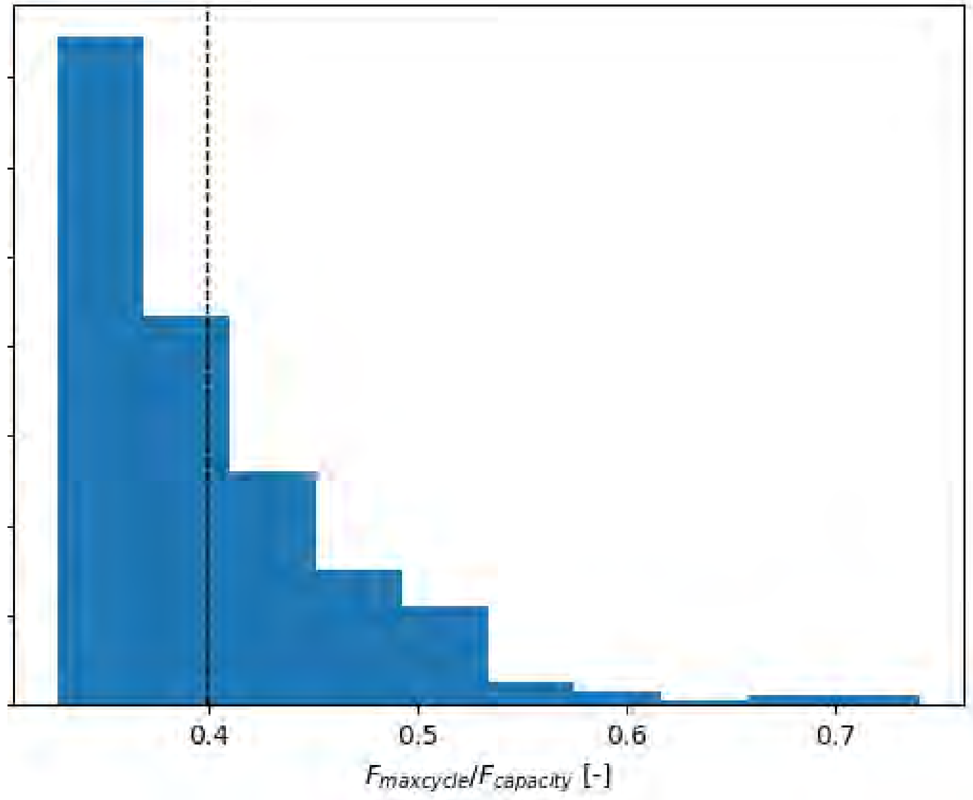
Mooring loads at anchor





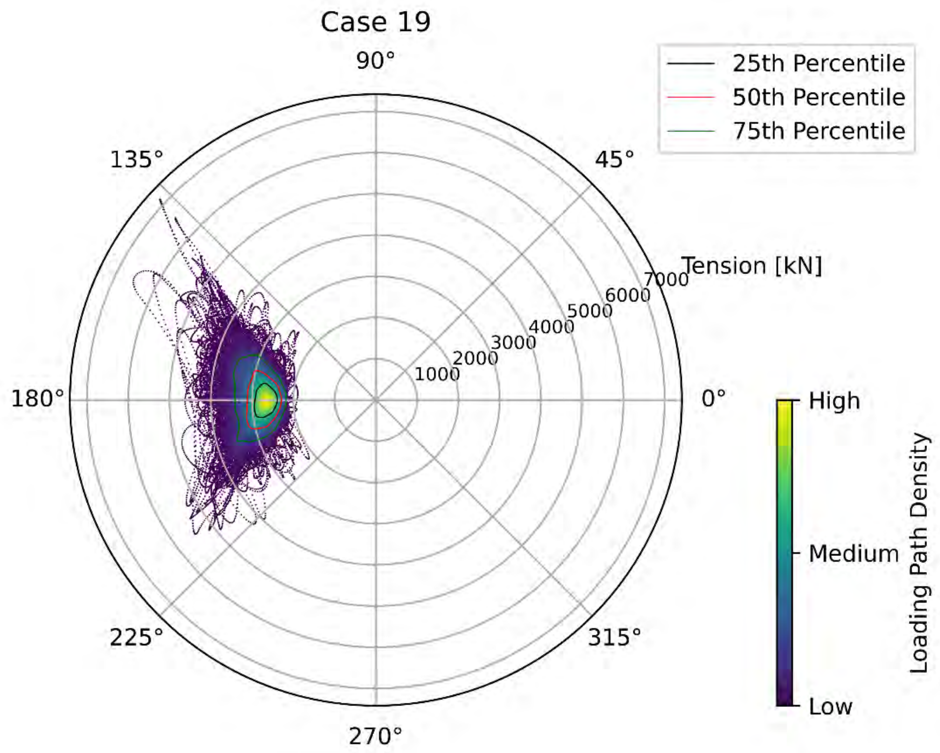
$$R = \frac{Min_{cycle}}{Max_{cycle}} = \zeta_C$$

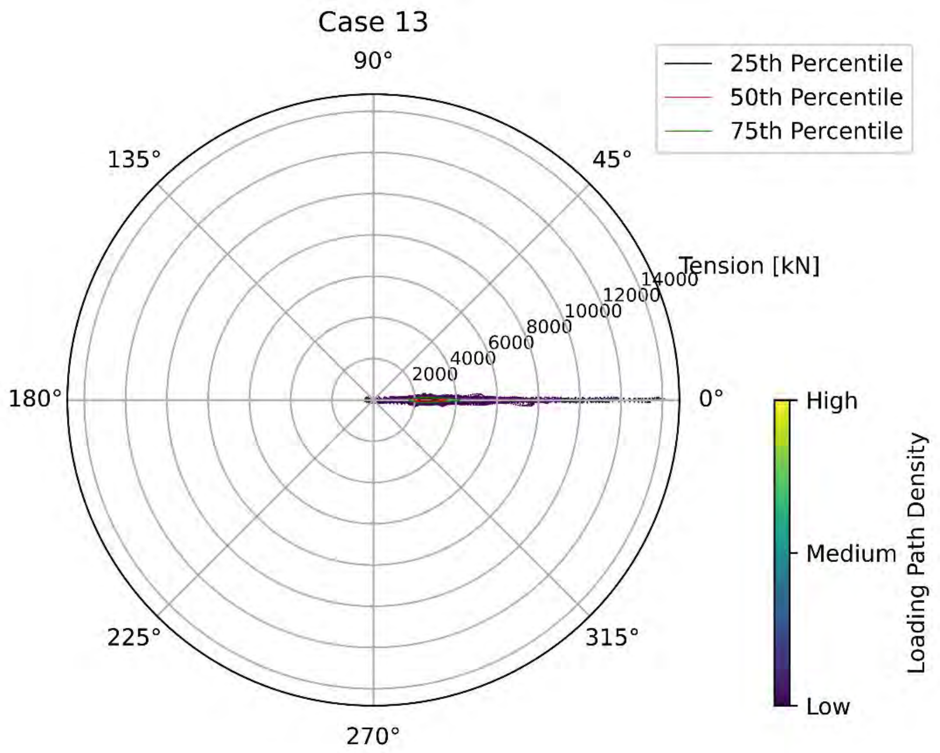


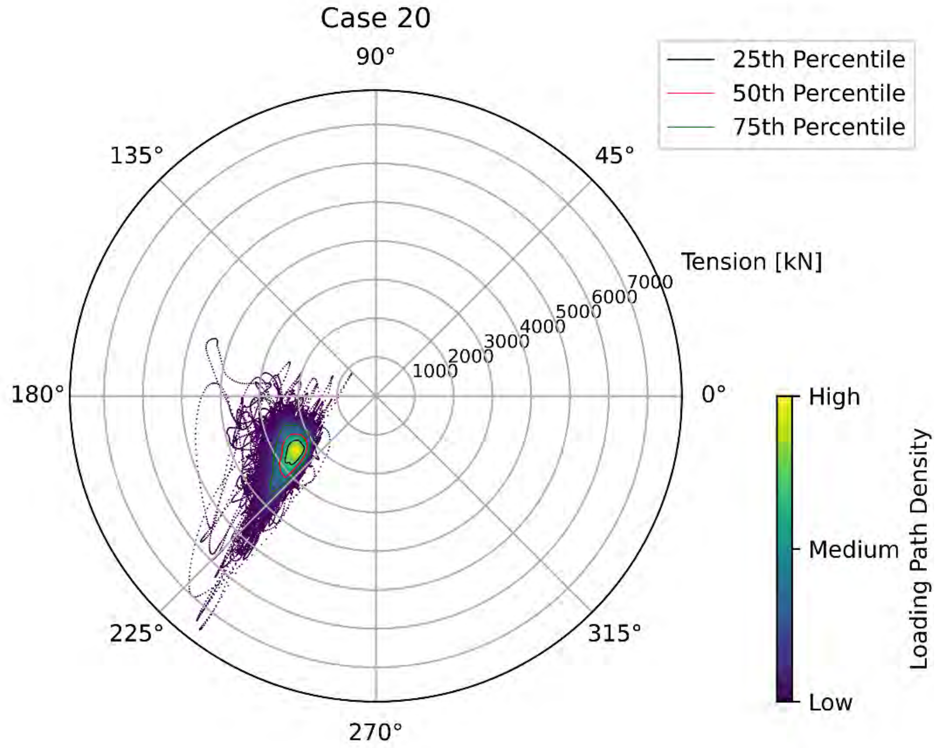


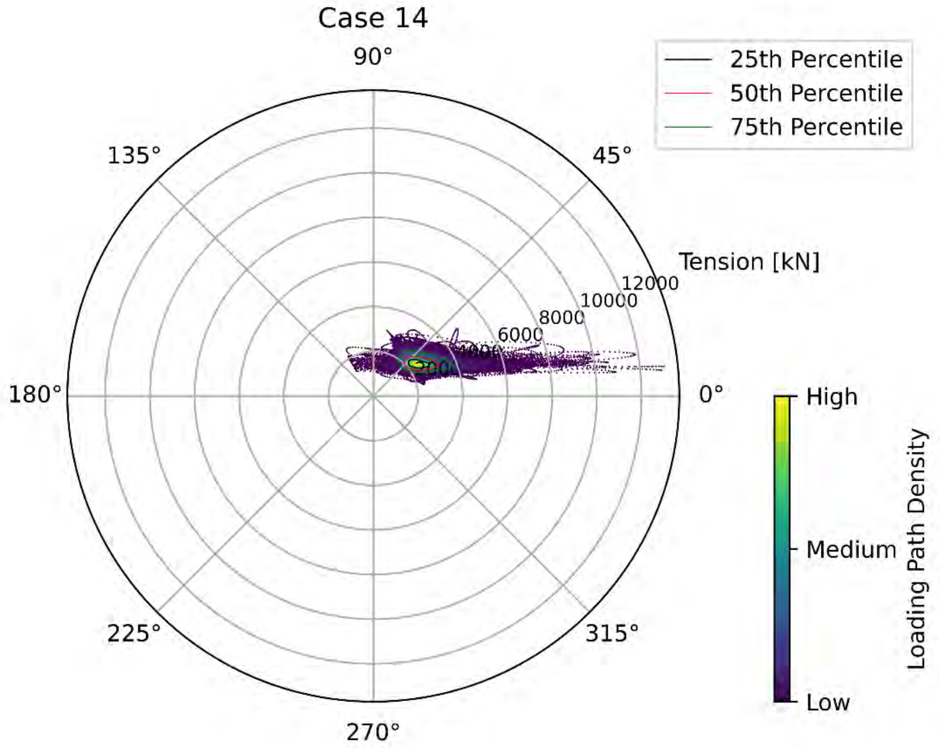
$$\zeta_b = \frac{H_{max}}{H_R}$$

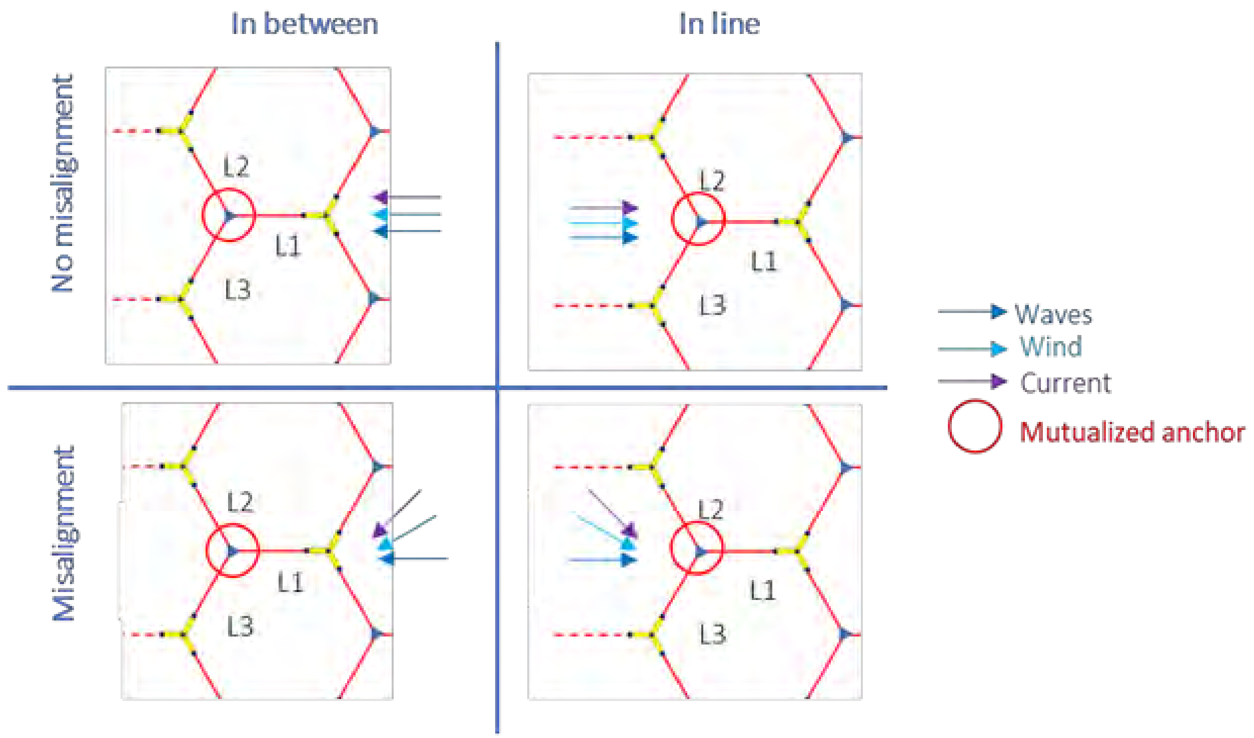
Mooring loads at anchor











Mooring loads at anchor - Conclusion

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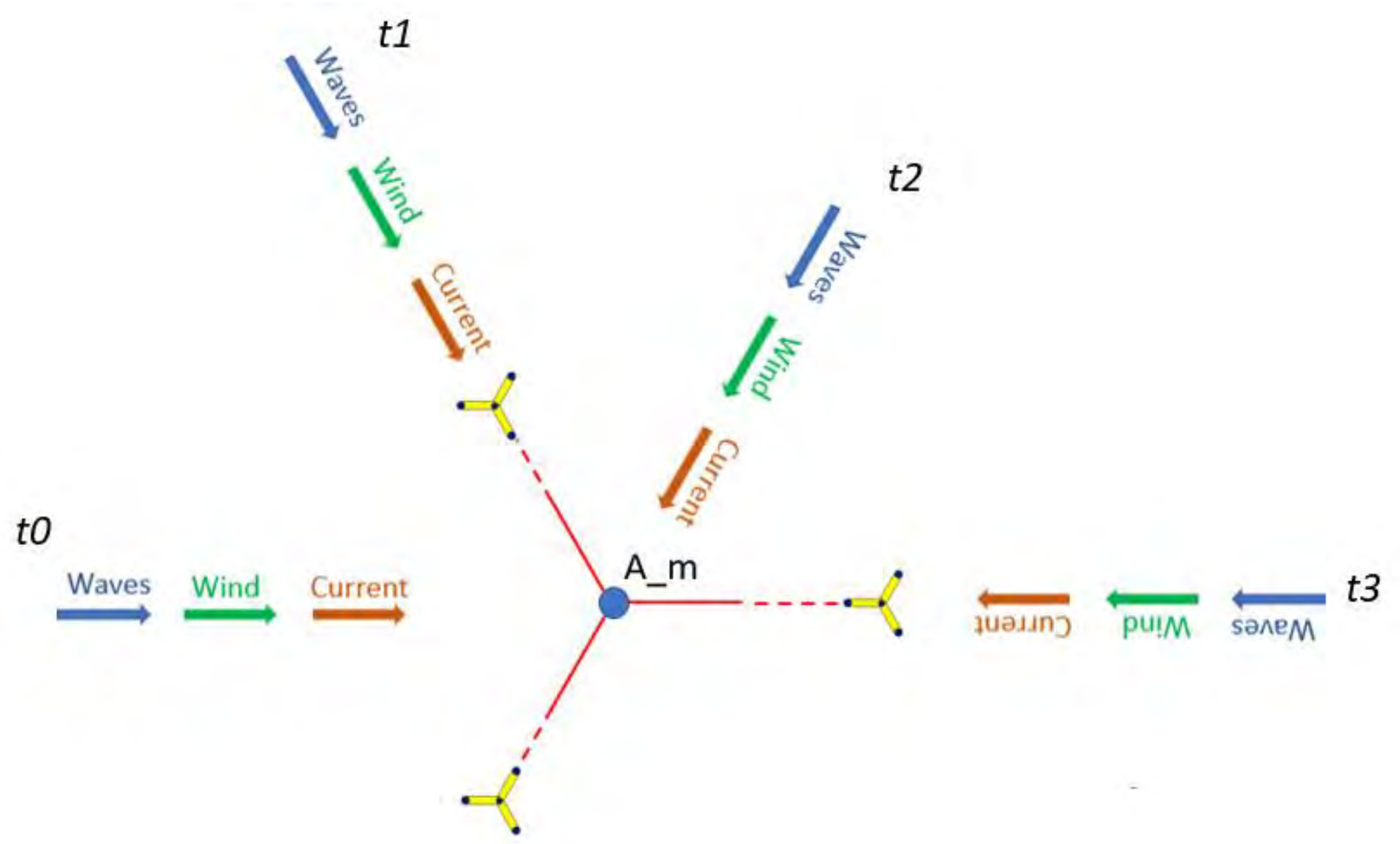
	Configuration	Type	Max(F_max) [kN]	Mean(F_max) [kN]	Fmean [kN]	Rmean [-]	Rmin [-]	Rmax [-]	F_M/M_mean [-]	Theta_mean [°]	Angular variation case 19 [°]
Water Depth 80 m	M.80.1	Catenary Chain									
	NM.80.1	Catenary Chain									
	M.80.2	Semi-taut Chain/Nylon									
	NM.80.2	Semi-taut Chain/Nylon									
	M.80.3	Semi-taut Chain/Nylon									
	NM.80.3	Semi-taut Chain/Nylon									
Water Depth 600 m	M.600.1	Taut Polyester									
	NM.600.1	Taut Polyester									
	M.600.2	Semi-taut Chain/Polyester									
	NM.600.2	Semi-taut Chain/Polyester									
	M.600.3	Semi-taut Chain/HMPE									
	NM.600.3	Semi-taut Chain/HMPE									

- **Type of configuration** (material, pre-tension) impacts the type of loading (directionality, R, Fm_c, extreme values) at anchor
- **Depending** on the environmental case (IB, IL, MIS..), type of loading are as well impacted
- **Fibers** with reduced stiffness are producing less variations than other materials

Mooring system design and anchor load analysis - Conclusions

- This work provided a wide range of data to represent shared and unshared loadings at anchor
- Depending on configuration, “loading types” are of different shapes at anchor
- Depending on environment type and directionality, similar “loading types” can be categorized at anchor (4 main categories)
- As loading time series were extracted from the mooring line design, some type of environmental load cases are not available, in particular for long term directionality variation



Mooring system design and anchor load analysis – Way Forward

- Include long term environment variation to create specific loading path for shared anchors
- Perform Mooring layout optimization for specific FOW sites
- Consider increased failure risk in the mooring configuration design
- Go further in the sharing concept by including shared mooring lines

Photo credit: DYohann Boutin