Energy Hub in the North Sea

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Artificial island; Building with Nature; Doggersbank; Sea defence; Sea level rise; Wave analysis; Wind farm.

ABSTRACT

The climate goals for 2020, that multiple countries in the world signed, are coming closer. Like many other countries, the Netherlands has difficulties reaching their climate goal. A solution came from the Paris agreement in 2015, which sets new goals for 2030, and eventually for the long term in 2050. This time the Netherlands is eager to reach their goal and amongst many other initiatives, a proposition came from TenneT, the country's national energy operator, to construct an island in the North Sea, functioning as a central "wind connector hub" to connect multiple offshore wind farms and distributing the energy more efficiently over the neighbouring countries. The goal of the project is to propose and analyse a preliminary design for the construction of that artificial island in the North Sea, capable of acting as a central energy hub. An analysis for optimum location for the island was performed based on maximum wind generation, shallow water depths, centrality to the North Sea countries, and environmental restrictions. Of various types of island considered, the reclamation type was chosen for preliminary design because it is the most cost effective for the location's water depths and the most commonly constructed island type. Following the scope definition, correspondence with TenneT and consultancy with subject experts at TU Delft was made to refine preliminary design outcomes. The preliminary design covers the analysis of available environmental and geotechnical data, safety approach, island shape, zones, elevations, analysis of alternative sea defence structures, building with nature measures, port and terminal design, and preliminary construction plan. The conclusions of this investigation cover practical issues, project risks and uncertainties, and opportunities to reduce costs are discussed.

1. Introduction

The ultimate goal of the project is to propose and analyse a preliminary design for the construction of an artificial island in the North Sea, capable of acting as a central energy hub. This Energy Hub in the North Sea project is a vision developed by TenneT (the national electricity transmission system operator of the Netherlands) that includes the construction of an artificial island in the North Sea to serve as a "wind-connector". The island will combine large scale wind farms with powerful interconnectors for higher system efficiency seeking to achieve CO2 reduction targets while attaining price convergence by connecting multiple North Sea countries to a shared grid [1].

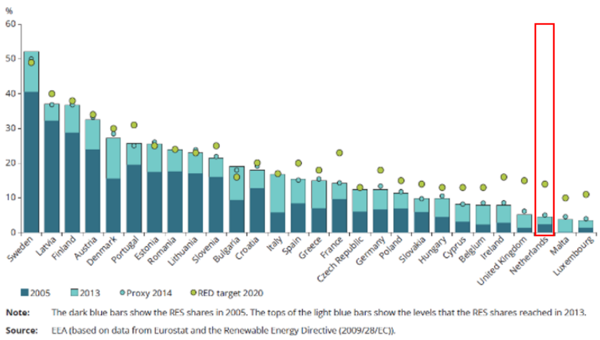


Figure 1. Actual and approximated RED shares in the EU-28 Member States in 2013 [2]

This idea came to life because of the 2015 United Nations (UN) Climate Change Conference in Paris. The Renewable Energy Directive (RED) goal to reduce emissions by 14% by 2020 would be unlikely. Also, under the Kyoto-protocol of 1997, the Netherlands agreed to decrease carbon emissions by 6% per year; however only 4.5% per year was achieved [3]. The European Environment Agency stated in multiple reports that the progress of the European Union (EU) member states remains slow [4][5]. The Netherlands ranks third lowest in RED shares among the EU, as seen in Figure 1 [2]. The reasons behind this are various, from the Netherland's petrochemical industry [6] to active agriculture [6][7] and a very high population density [8], amongst others.

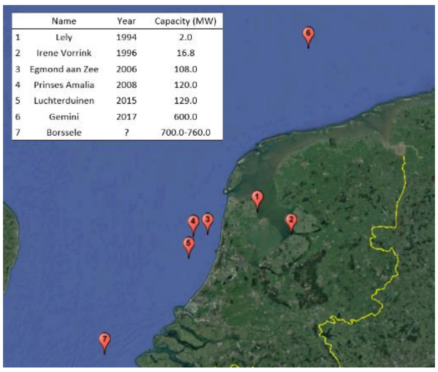


Figure 2. Offshore wind farms in the Netherlands

Despite the negative predictions and challenges, the Netherlands is very active in the research of wind energy. In 1973, the first wind turbine study took place [9] as a result of the oil crisis and the research field hasn't been sitting still ever since. Figure 2 shows the windfarms currently present in the

Netherlands, and even more are planned [10] [11] [12].

Future windfarms could be planned further offshore where there is a high capacity of wind energy, suggesting that more integrated infrastructure is necessary. The proposed concept includes North Sea infrastructure that provides: optimal energy transmission, further European market integration, and higher system efficiency between the Netherlands, Belgium, Denmark, Germany, Norway, and the U.K. [13]. The concept follows a 'Hub and Spoke' model, which is a network of traffic along many spokes connected to a central hub [13]. An artificial island referred to as the Energy Hub is the proposed investment for long-term cost savings of an international energy market.

For this research, the given location is in the Doggersbank, which can be seen in Figure 3, because it is a shallow point in the North Sea, its centred location, and the planned windfarms in the proximity because of great wind conditions. The exact location is 54°40'33" N/02°21'28" E.

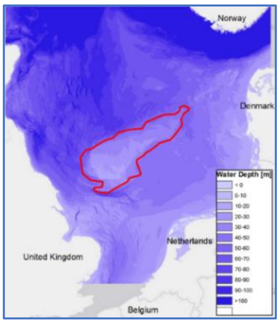


Figure 3. Doggersbank

2. Site evaluation

Although a shallow location, the area is located in the middle of the North Sea and has harsh environmental conditions.

The water levels are determined by analysing data from buoy D15 (54.3247°N/2.934612°E) [14].

Table 2. Water levels

Water level	Elevation [m]
Highest Astronomical Tide (HA)T	1.19
Mean High Water (MHW)	0.42
Mean Sea Level (MSL)	0.00
Mean Low Water (MLW)	-0.40
Lowest Astronomical Tide (LAT)	-1.04

The wave climate is a significant boundary condition and drives the sea defence design. A total of six nearby wave buoys are chosen and with the 'Peak over Threshold' method, the wave characteristics are determined [15]. These were then analysed in SWAN 1D, to simulate nearshore conditions. This can be seen in Table 1 for short and long term.

Table 1 also shows the wind direction which is also shown in the figure below. The dominant wind direction is South West.

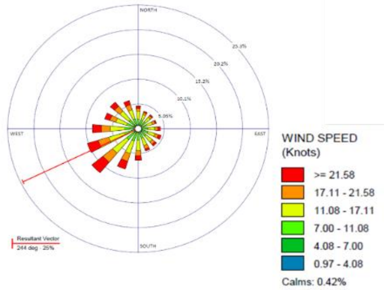


Figure 4. Wind rose

3. The island

The island has a given area of 6km². There are multiple things to consider for this preliminary design. Firstly, the type of island is considered. Between all island types, the reclamation type island is preferred, because of its cost-efficiency [16] and because it has been proven a reliable way of

Table 1. Wave and wind data

Buoy Name	Return period	Wind		Offshore conditions				Nearshore conditions			
		Velocity [m/s]	Dir [°N]	H_s [m]	T_m [s]	T_p [s]	Dir [°N]	H_s [m]	T_p [s]	T_m [s]	Incidence angle [°]
North	5	18.94	-30	7.49	13.19	14.11	-18	5.76	13.89	9.08	1
	10,000	29.11	-30	13.76	17.04	18.23	-18	7.41	19.28	10.33	6
East	5	17.04	104	4.44	9.63	10.59	94	2.65	11.16	8.13	4
	10,000	24.33	104	7.24	11.85	13.03	94	4.45	12.45	10.06	4
South	5	21.68	-144	4.81	9.20	10.12	-160	4.80	10.00	7.10	23/40
	10,000	31.48	-144	7.78	10.98	12.07	-160	6.73	12.45	8.31	26/43
West	5	20.98	-92	5.14	9.75	10.73	-86	4.92	11.16	7.16	22
	10,000	30.27	-92	9.08	12.25	13.48	-86	7.27	13.89	8.48	21

constructing artificial islands all over the world [17]–[19].

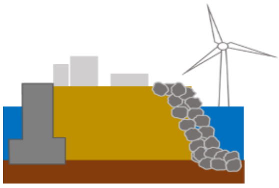


Figure 5. Sketch of reclamation type island

The island's shape is to be considered. A circular shaped island might give the most optimal area, easiest construction, and shortest length of sea defence structures. In this study, the shape was optimized to follow the bathymetry and 'raising it up' above sea level. This could ensure a more natural flow of currents and minimizing the depth of sea defence. Also, this could minimize the cost of the island. The island's shape is seen in Figure 6. The location is chosen North of the local shallow area, so future expansion is possible in an area protected from the highest waves.

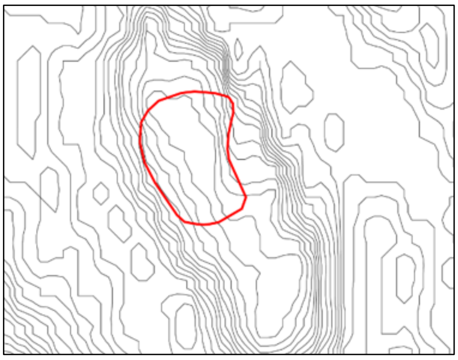


Figure 6. Island shape, with bathymetry

Another issue is the safety approach to be followed. One of the main philosophies to be followed is 'never break down', which is an important criterion for TenneT. Rather than constructing the entire island to satisfy this requirement, the approach used was to protect the critical infrastructure, and allow flooding during extreme events to areas with less strict damage requirements. This leads to a design of the island at different elevations, where the lower elevation functions as an allowable flooding area during extreme events. The inner, higher elevated area is protected by a levee and prevents flooding of all valuable facilities. Figure 7 shows the both situations, where the double layer defence approach could reduce the height of the sea defence and total fill material needed for the island.

Furthermore, the area is divided into different zones according to their function, as seen in Figure 8. The energy infrastructure, supporting infrastructure, and living areas are located behind the leveeand should be flood-protected at all times. The cable infrastructure is important, because it contains the wind turbine cables and the cables distributing energy towards the mainland. These go over the sea defence to a landing point in the flooding zone and are redistributed towards the cable infrastructure, within the non-flooding area. The cables include approximately 80 wind turbine cables and 16 interconnecting cables.

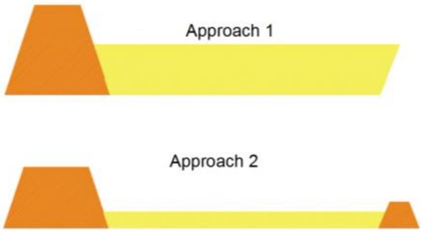
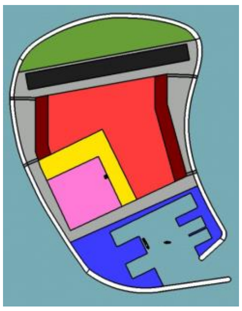


Figure 7. Safety approach, single layer defence (up) vs. double layer defence (down)

The flooding areas of the island are the port area, the nature area and the airport runway. There is a heliport located in the living area, which functions as emergency transport or evacuation. Based on guidance with project advisors, flooding once or twice during the lifetime of the island is considered acceptable.



Zone	Area [km²]	
Harbour & Port	2.3	
Airport & Heliport	0.3	
Living and recreation	0.4	
Energy infr.	1.2	
Cable infr.	0.1	
Supporting infr.	0.3	
Nature	0.5	
Other	0.9	
Total	6.0	-

Figure 8. Island zones and areas

The 6km² island area is a given for this preliminary design. However, this leaves some space for 'other' facilities. If the size per area is fine-tuned, it is concluded that an area of 3.7km² may be satisfactory.

4. Building with nature

The shape of the island was already mentioned as one of the 'building with nature' measures. The Doggersbank area is part of Natura 2000, an initiative to protect local habitats of plants and animals, so if a construction is made there, some more measures should be taken. One idea is the placement of oyster beds on the toe of the sea defence structures. They are capable of modifying their own habitats, and that of other species [20]. Historically, oysters lived in that part of the North Sea, but have diminished due to overfishing [21]. This could be a great opportunity to reintroduce them into the area.

The Dutch project 'Maasvlakte 2' in the port of Rotterdam is a great example of building with nature, where a combination was made between a beach dune and a concrete armour submerged breakwater [22], creating as much natural value as possible, as seen in Figure 9. The implementation of a gravel beach at the island site could also be considered, if the sea environment would allow it. This is not researched in this preliminary study as modelling is required to confirm its feasibility.

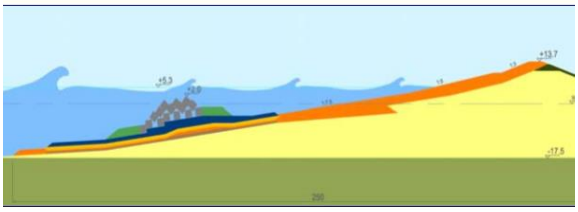


Figure 9. Concept of Maasvlakte 2

If concrete elements are used for the sea defence, it is possible to use eco-concrete, or some other form of recycled and/or ecological concrete.

5. Sea and flood defence

The design approach for the sea defence structures is to minimize the cost and the maintenance, while maximizing the natural value. Multiple different structures are investigated: rubble mound breakwater, Xblocs, gravel beach, caisson structures and a 'Maasvlakte 2' style hard/soft breakwater. For each side of the island, alternatives are investigated with a design analysis and cost. These can be seen in Table 3.

Table 3. Sea defence options (green cells are pros; red ones are cons and yellow is neutral)

		Maintenance	Flexibility	Cost [10^6 €/km]	Failure mode	Foot Print [m]	BwN
North	Xbloc Armour Rubble Breakwater	Rare maintenance, maybe some at the toe	Easy adaptation to SLR, settlements	55	Instantaneous failure Armour layer, repairable	52	Eco Xblocs
	Vertically Composite Caisson Breakwater	Rare maintenance	No flexibility due settlements	145	Instantaneous failure	40.6	No room for marine species
East	Rock Armour Rubble Breakwater	Supply	Easy adaptation to SLR, settlements	38	Quick repair of different layers	70	Natural area for fauna
	Gravel Beach	Nourishment needed, longshore currents	Easy adaptation to SLR, settlements	24	Quick repair of different layers	256	Area for fauna, oyster reef
South	Xbloc Armour Rubble Breakwater	Rare maintenance, maybe some at the toe	Easy adaptation to SLR, settlements	48	Instantaneous failure Armour layer, repairable	53	Eco Xblocs
	Hard/Soft Breakwater	Maintenance needed, longshore currents	Easy adaptation to SLR, settlements	45	Quick repair of different layers	210	Area for fauna, oyster reef
West	Xbloc Armour Rubble Breakwater	Rare maintenance, maybe some at the toe	Easy adaptation to SLR, settlements	55	Instantaneous failure Armour layer, repairable	52	Eco Xblocs
	Hard/Soft Breakwater	Maintenance needed, longshore currents	Easy adaptation to SLR, settlements	48	Quick repair of different layers	222	Area for fauna, oysters

6. Harbour

The port is designed for a combination of four different types of vessels, mainly functioning as maintenance vessels for the wind turbine farms. A summary of results can be seen in Table 4.

Table 4. Determination port dimensions

	Vessel	Length Overall [m]	No. of Vessels	Quay length [m]	Quay Area [m²]
1	General Cargo vessel [20000 DWT]	160	4	800	20,000
2	CTV (Crew Transfer Vessel)	25	72	2,250	22,500
3	Supply Vessels - Standard Supplies	82	5	513	12,813
4	SOV	80	18	1,800	45,000
	Total			6000	110,000

7. Construction plan

A lot of dredging works will have to be executed. Preferably, sand will be extracted from somewhere close (<600km) so a hopper dredger can transport it to the location and dump it in place until the water depth approaches the vessel draft. After, rainbowing is a good option, yet it takes longer. Labourers will be at sea for extended periods of time and there should be an extra ship for accommodation.

This preliminary design is still in the early stages, so making a detailed plan of construction is difficult. Following is a vague estimate of a construction plan:

Year 1: If necessary subsoil ground improvement is required, they will take place within the first year. Year 2: Work starts with the construction of the most Northern sea defence. This must happen between April and August to avoid construction during winter. Year 3: The dumping of the first few million m³ of sand can start. If needed, a curtain needs to be installed to prevent the loss of sediment depending on the current velocities. Near the end of this year, the Northern breakwater should be finished.
Year 4: The construction of the Western breakwater starts and enhances sheltering of the increasing fill. It is expected that rainbowing has started and the fill has reach higher than MSL. Construction of the port quay wall can start.
Year 5 and 6: The works on the Western breakwater continue from North to South and should be finished in the sixth year, moving onto the Southern breakwater. The filling of the island can be concentrated in the port area with the goal of having a surface on which to operate by the end of year 6.
Year 7 and 8: The Eastern breakwater can be constructed, completing the sea defence. The topside of the island should be constructed to the desired elevation with ground improvements completed capable of supporting preliminary civil works. Additionally, construction of the inner levee is completed together with the area within.
Year 9: It is assumed that the ground improvements are complete and infrastructure work can move relatively quickly considering the port is operational. Year 10 and 11: The energy infrastructure, supporting and living infrastructure, airport, nature area, are completed in time to begin operations in 2050.

8. Cost

For the estimation of the cost, two assumptions are made. 1)The cost only includes the material of the island and excludes the civil works, infrastructure, construction cost and design works. 2)An inflation rate of 1.8% is assumed for construction between 2040 and 2050 [23]. This is seen in **Fout! Ongeldige bladwijzerverwijzing.**. The total cost, including the inflation rate and a contingency factor is estimated on 2.63 billion euros.

***Table 5**: Cost estimation*

Item	Quantity	Unit	unit price [€]	Total price (10^6 €)
Levee	6.25	km	1.40	8.75
Fill	108,758,100	m³	4.00	435.03
Floating jetties	2192	km	700.00	1.53
Quay	3750	km	38,360.00	143.85
South	1.8	km	48.00	86.40
West	2.8	km	55.00	154.00
North	2.5	km	55.00	137.50
East	2.6	km	38.00	98.80

9. Project risks

A risk analysis for the sea defence structure is executed. The analysis is based on the probability of the critical area to flood. The flooding scenario evaluated includes failure of the levee that will cause flooding of the effective area. The levee is going to be uniformly designed with the same probability of failure for all sections.

The individual risk is determined for this scenario using the following probability model [24]:

$$IR(x,y) = \sum_{i}^{n} P_i F_{D,i}(x,y)\,(1 - F_{E,i})$$

In which: IR(x,y) = the individual risk
P_i = the probability of the scenarios
$F_{D,i}$ = the mortality fraction
$F_{E,i}$ = the evacuation fraction, assumed to be 0, as the location is in the middle of the North Sea

According to ISO2394, an annual fatality rate of 1E-6 is accepted [25]. The results of this analysis are given in Table 6, which shows that only a return period of 10,000 years (for which the island's defence is calculated) is acceptable.

***Table 6**. Individual risks per return period*

Return Period [years]	Individual Risk	Acceptable?
1,000	8.5E-6	No
5,000	1.7E-6	No
10,000	8.5E-7	Yes

Next, a top 10 of the expected risks on the island is given, this is seen in Table 7.

Finally, there is a political risk. Doggersbank is located within the UK's maritime borders. It is not impossible to construct a Dutch island there, but it

Table 7. Top 10 risks of the island during construction and operation

Risk	Description	Probability	Effect
1	Failure of the inner dike (during a flood event)	Low	Flooding of the inner zone, damage to high voltage equipment, island is not operational, loss of life.
2	Large storm event	High	island is partly not operational, flooding of the controlled flooding area, the port and airport are unusable.
3	Fatal or near-fatal work accident	Medium	A person gets wounded badly during labour, with no high medical care.
4	Unfavourable construction circumstances	High	Delayed construction, destruction of works, increased cost.
5	Fire	High	Destruction of facilities, island is partly not operational, spreading of fire, injured people.
6	Settlement	Low	Failure of the island construction, damage to buildings
7	Environmental	Medium	Not a direct risk, but the risk that there will be more environmental damage than acceptable.
8	Ship accident in the port	Medium	Port becomes (partly) unusable.
9	Failure of the outer sea defence	High	Too much flooding of the controlled flooding area, more failure of the sea defence.
10	Earthquake	Low	Too much settlements and structural failure of the island.

comes with several uncertainties, especially in present times with the '*Brexit*' political issue. This is however out of the scope of this study.

10. Design uncertainties

- The buoy data was limited in location and quantity. The only useful buoy has only 8 years of data. From this small dataset, the storm surge is incomplete and the SLR was extrapolated to predict 150 years in the future.
- Both physical models (for the sea defence) and computer models (current model, interactions of mechanisms, shape, etc.) are needed for this project, which was not done for this study.
- There is a big uncertainty in the materials used, mainly for the geotechnical analysis and the cost. The obvious choice of regular sand and rocks was made, but maybe other materials and even recycled materials can be used.
- To full consider the design uncertainties, the analysis of a full probabilistic model needs to be done.

11. Conclusion

Building an efficient and productive wind energy market in the North Sea has been kicked off by TenneT, making the ambitious European energy goal a reality. At the centre of the electricity system is the proposed artificial island, which was only a concept at the start of this investigation.

After coordination with both TenneT and subject matter experts at TU Delft, it was found, there do not appear to be any obvious physical or regulatory realities preventing the project from moving forward under this scope, given the project risks.

This preliminary study can be seen as a framework of how to minimize costs and maximize value of the island. This design serves as a starting point for future research on design alternatives and how to address the uncertainties and risks.

12. Future research

During this design process, the following items were found to be important for more extensive research:

- Construct a safety approach; International guidelines (e.g. ISO) along with new Dutch standards can be used, however, expert judgement is required to possibly enhance existing codes.
- Maximize cost effectiveness; A thorough understanding of how to work with existing bathymetry, water levels, wave and wind conditions is the most effective way to reduce costs. Also, by refining island infrastructure requirements, the area may be reduced from the given 6km².
- Optimize island shape; The island shape was assumed to be an extension of the bathymetry here. Later, different shapes should be analysed and the optimum should be determined.
- Incorporate building with nature measures; There was no extensive research to the BwN possibilities. This could have a great advantage for the cost and the environmental impact.
- Allow for adaptive design; This is achieved by incorporating design features that minimize future investment into expansion.

(June 2017)

References

[1] M. Kroon, "Future North Sea Infrastructure," 2016.

[2] European Environment Agency, *Renewable energy in Europe — recent growth and knock-on effects*, no. 1. 2016.

[3] Centraal Bureau voor Statistiek Nederland, "Nederland en de Kyoto-doelstelling," 2013. [Online]. Available: https://www.cbs.nl/nl-nl/achtergrond/2013/04/nederland-en-de-kyoto-doelstelling. [Accessed: 15-Mar-2017].

[4] European Environment Agency, *Greenhouse gas emission trends and projections in Europe 2012, EEA report No 6/2012*, no. 6. 2012.

[5] European Environment Agency, "Trends and projections in Europe 2016: Tracking progress towards Europe's climate and energy targets," 2016.

[6] B. Coates, "How green is Holland? From carbon emissions to climate change," *The Independant*, 21-Sep-2015.

[7] The World Bank, "Methane emissions (kt of CO2 equivalent)," 2012. [Online]. Available: http://data.worldbank.org/indicator/EN.ATM.METH.KT.CE?locations=EU&year_high_desc=true. [Accessed: 15-Mar-2017].

[8] The World Bank, "Population density (people per sq. km of land area)," 2015. [Online]. Available: http://data.worldbank.org/indicator/EN.POP.DNST?end=2012&start=2012&year_high_desc=true. [Accessed: 15-Mar-2017].

[9] B. Verhees, R. Raven, F. Kern, and A. Smith, "The role of policy in shielding, nurturing and enabling offshore wind in The Netherlands (1973-2013)," *Renew. Sustain. Energy Rev.*, vol. 47, pp. 816–829, 2015.

[10] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties., "Plan van Aanpak Energiebesparing Gebouwde Omgeving," p. 12, 2011.

[11] Ministerie van Infrastructuur en Milieu, "Kamerbrief over Windenergie op zee," *Tweede Kamer der Staten-Generaal*, p. 12, 2014.

[12] Ministerie van Volkshuisvesting Ruimtelijke Ordening en Milieubeheer, "Windmolens in Nederland op land," 2010.

[13] TenneT, "North Sea Infrastructure," 2016. [Online]. Available: http://www.tennet.eu/nl/onze-kerntaken/innovaties/north-sea-infrastructure/. [Accessed: 16-Mar-2017].

[14] J. Bosboom and M. J. F. Stive, *Coastal Dynamics I (lecture notes CIE4305)*. 2015.

[15] H. J. Verhagen and J. P. Van den Bos, *Breakwater design*, no. January. Delft University of Technology, 2017.

[16] D. J. Zwemmer, "Guidelines for Design and Construction of Artificial Islands." p. 277, 1998.

[17] Discovery Channel, "Extreme Engineering: Hong Kong International Airport," 2003.

[18] A. Dhaundiyal, "Palm Tree Island in Dubai, UAE," 2016. [Online]. Available: http://doontech.com/palm-tree-island/. [Accessed: 01-Apr-2017].

[19] National Geographic, "MegaStructures - Kansai International Airport," 2004.

[20] K. Bouma, Reise, T. J. Olenin, and T. Ysebeart, "Coastal habitat engineers and the biodiversity in marine sediments," 2009. .

[21] J. W. P. Coolen, *North Sea Reefs*. Brussels, 2017.

[22] Port of Rotterdam, "Maasvlakte 2." [Online]. Available: https://www.maasvlakte2.com/nl/index/. [Accessed: 01-Apr-2017].

[23] City of Lincoln, "Calculating Inflation Factors for Cost Estimates." .

[24] S. N. Jonkman, R. D. J. M. Steenbergen, O. Morales-Nápoles, A. C. M. W. Vrouwenvelder, and J. K. Vrijling, *Probabilistic Design: Risk and Reliability Analysis in Civil Engineering*, 3rd ed. TU Delft, 2016.

[25] *ISO 2394: General principles on reliability for structures*, 4th ed. Geneva, 2015.