Objectifying Building with Nature strategies

Towards scale-resolving policies

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Abstract

By definition, Building with Nature solutions utilise services provided by the natural system and/or provide new opportunities to that system. As a consequence, such solutions are sensitive to the status of, and interact with the surrounding system. A thorough understanding of the ambient natural system is therefore necessary to meet the required specifications and to realise the potential interactions with that system. In order to be adopted beyond the pilot scale, the potential impact of multiple BwN solutions on the natural and societal systems of a region need to be established. This requires a 'reality check' of the effectiveness of multiple, regional-scale applications in terms of social and environmental costs and benefits. Reality checking will help establish the upscaling potential of a certain BwN measure when addressing a larger-scale issue. Conversely, it might reveal to what extent specific smaller-scale measures are suitable in light of larger regional-scale issues. This paper presents a stepwise method to approach a reality check on BwN solutions, based on the Frame of Reference method described in a companion paper (de Vries et al., 2021), and illustrates its use by two example cases. The examples show that a successful pilot project is not always a guarantee of wider applicability and that a broader application may involve dilemmas concerning environment, policy and legislation.

KEYWORDS

Building with Nature, ecosystem services, frame of reference, objectification, design, solutions

1. Introduction

Building with Nature (BwN) solutions utilise services provided by the natural system and/or provide new opportunities to that system (De Vriend and Van Koningsveld, 2012). In order for BwN-solutions to be effective, the functioning of the system in which they are embedded needs to be well understood. The BwN philosophy is applicable to engineering infrastructure development in a variety of surface water systems (De Vriend et al., 2015, Bridges et al., 2018, Laboyrie et al., 2018), but also at different scale levels, from a single project to regional-scale strategies. This also means that the system functioning at this larger scale needs to be considered and understood.

Where BwN solutions are supposed to fit into such a larger-scale strategy, objective evaluation beyond isolated pilot implementations is required to demonstrate the larger-scale functionality of multiple smaller-scale interventions. On the other hand, it is important to establish which smaller-scale engineering solutions are suitable for application at the larger scale (considering the desired overall effect at the system scale, which local solutions are likely to be effective?). Important evaluation criteria are the societal and environmental costs and benefits.

The Frame of Reference (FoR) method described in a companion paper (De Vries et al., 2021) provides an explicit framework to streamline the design of water infrastructure and other processes involving complex decision making. It starts from a clear definition of strategic and operational objectives. This method can be equally applied to the development phases of individual projects and to multiple projects at the regional scale. De Vries et al. (2021) demonstrate the applicability of this method in a project context. Application of the FoR method across different scales provides an important reality check for the viability of individual BwN solutions and the overall strategy to which they contribute. In that sense, such an assessment can become a key enabler for the wider acceptance of BwN-based strategies. This scale resolving scope, however, has yet to receive the same level of attention as the project/pilot scope. The objective of this paper is to fill this gap by applying the FoR-method in a step by step process to two cases with different types of measures in different environmental settings, in order to reality-check the benefit of upscaling the implementation of BwN at a regional-scale. Subsequently, we consider a broader spectrum of BwN solutions and see what larger-scale strategic objectives they aim to meet.

2. Reality-checking regional-scale BwN solutions

The "Frame of Reference" approach

The Frame of Reference (FoR) approach (Van Koningsveld, 2003; Van Koningsveld et al., 2003; Van Koningsveld and Mulder, 2004) was developed to match specialist knowledge with end user needs by making the essential components of a decision problem explicit. In that way, the FoR approach streamlines discussions between different actors, following an interactive process to achieve ongoing refinement. Fundamental to this approach is the definition of clear objectives at strategic and operational levels, reflecting key elements of the policy strategy. For the operational phase, indicators are defined to verify whether or not the objectives are met. The operational phase requires specification of the following elements:

- the Quantitative State Concept (QSC),
- a benchmarking procedure,
- an intervention procedure, and
- an evaluation procedure.

These elements interact as indicated in Figure 1.

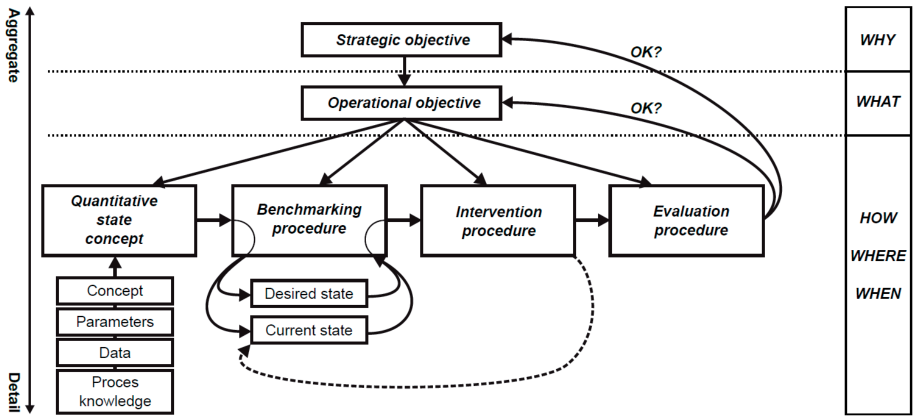

Figure 1. The 'basic Frame of Reference template' (modified from: Marchand, 2011)

Steps for scale resolving application of the FoR method

When applying the FoR method in a scale resolving management approach, recurring procedural steps are:

1. Define the regional-scale strategic and operational objectives and break down the realisation strategy into a number of logical elements (projects).

2. Specify strategic and operational objectives for each project individually.
3. Quantify the performance of each project individually in light of these objectives.
4. Determine to what extent each project meets its individual objectives.
5. Check if the combination of projects (the scheme) achieves the overarching strategic and operational objective(s), using plausible quantitative estimates of the effects.
6. Check how the designed scheme fits into the regional governance context.

Each individual project can be designed as a BwN intervention. The six-step objectification process proposed in the companion paper by De Vries et al (2021) can be used for that purpose. We will follow these steps in the following evaluation of the two example projects.

Sandy strategies for coastline maintenance (coastal, soft, abiotic)

Step 1: Large-scale strategic and operational objectives, and breakdown of the realisation scheme

The sandy shores of the North Sea Coast in the Netherlands have long been eroding as a result of the combined effects of sea level rise, reduced supply of river sediment and ongoing land subsidence. After finalisation of the Delta works, attention to countering this ongoing erosion has increased. This materialised into a policy to preserve functions and values in the coastal zone (*strategic objective*). An extensive study of coastal processes at various time and space scales (Stive et al., 1990) revealed that maintaining the coastline requires adding an amount of sand of the order of 10 million m^3 per year. Therefore, the Netherlands government established a sediment management policy aimed at keeping the coastline at its 1990 position, the Basal Coastline (BKL) (*operational objective*; see Van Koningsveld and Mulder, 2004). To that end, a volumetric coastline definition was laid down in law.

Note that this maintenance policy is different from interventions ensuing from the regular coastal safety assessments. The latter focus on dune erosion during a mega-storm event, rather than on the sand volume in the coastal profile.

The maintenance policy is presently implemented by means of beach or shoreface nourishments along the Dutch coast wherever the coastline recedes beyond the BKL. The design lifetime of these nourishments is generally some 5 years. Evaluation of this policy led to the conclusion that this approach meets the objectives as far as the upper shoreface is concerned, but that not enough sediment reaches the lower shoreface to balance erosion there. This led to a *second strategic objective*: to maintain the lower shoreface (the coastal foundation; see Mulder et al., 2007).

Step 2: Strategic and operational objectives per nourishment project

The operational objective of each maintenance nourishment is to locally prevent structural coastal erosion. The volume of an individual nourishment was typically 1-5 million m^3, which was sufficient to achieve the operational objective for a period of 3-5 years. The Delta Committee (2008), however, anticipated a significant increase in nourishment volumes, from the present 10 million m^3/year to 40 - 85 million m^3/year, depending on the rate of sea level rise. This might necessitate larger nourishments and/or new nourishment methods. In line with the BwN-philosophy, the idea emerged to concentrate the regular nourishments in space and time, relying on natural processes (currents, waves) to distribute the sediment over the wider coastal system. As compared with smaller-scale nourishments repeated every 3 to 5 years, utilising this ecosystem service was expected to achieve the *operational objective* in a more sustainable manner. It was expected to reduce the ecological and CO2 footprint of the nourishment policy while creating opportunities for recreation and nature development, thus providing ecosystem services and addressing *additional operational objectives*.

Figure 2. The Sand Motor; left: after placement in 2011; right: in 2017. (source: Rijkswaterstaat Beeldbank, https://beeldbank.rws.nl/; photos Joop van Houdt)

Step 3: Quantification of Project performance

In 2011 an experimental 21.5 million m^3 mega-nourishment project called the Sand Motor was implemented in front of the Delfland coast (Stive et al., 2013, *Figure* 2). The design process ultimately resulted in a hook-shaped peninsula that would provide space for juvenile dune formation and resting areas for birds and seals, with a shallow lagoon that would provide habitat to juvenile fish and other species. Part of the sand would be transported onshore by wind, promoting the dune formation along the beach. The hook-shape was furthermore assumed to be attractive for beach recreation. In anticipation of coastal science and management interest, an extensive monitoring program was carried out including deployment of a video observation tower on the beach. Based on pre-project sediment balance and numerical model studies, the project was framed as being sufficient for 20 years of coastal maintenance.

The overarching objective of the Sand Engine experiment was to test whether the anticipated benefits of such a concentrated mega-nourishment, viz. auto-distribution by natural processes, the development of habitats and realization of recreation potential, would indeed materialise. This was established via monitoring programs, measuring campaigns and multidisciplinary research programs (see Luijendijk and Van Oudenhove, 2019).

Step 4: Objectives met?

Although the objectives of the Sand Motor were not formulated sharply enough to allow for quantitative evaluation (e.g. De Weerdt, 2015), Luijendijk and Van Oudenhove (2019) conclude from the results of these efforts that the effects of the Sand Motor are partly beyond expectation (recreation, biodiversity) and partly less so (ecosystem recovery, aeolian transport into the dune area, juvenile dune formation on top of the nourishment). Also, the expectation that in the coastal cell between Hook of Holland and Scheveningen no further nourishments would be needed for 20 years turned out to be unrealistic: nature takes time to distribute the sand alongshore and, in the meantime, areas further away from the Sand Motor may need intermediate nourishing in the years to come. Yet, the number of nourishments in this coastal cell would be significantly less without the Sand Motor, which means less costs (mob/demob), less energy expenditure and less CO2-emissions. Also, because the sand is deposited in a much thicker layer, the environmental impact of the Sand Motor, in terms of disturbed seabed / benthic organisms, is much smaller as the nourishment footprint scales inversely proportional to its height. Table 1 illustrates this observation, showing that the footprint of the Sand Motor is approximately similar to the footprint of a regular nourishment area. As the regular nourishment has to be repeated another 8 times to realise the same total sand volume, its total impact becomes much larger – especially as the recovery time of benthic communities in the nearshore (~4-6 years) aligns with the return frequency of classic nourishment schemes.

	volume (10^6 m^3)	volume (m^3/m)	longshore length (m)	cross-shore width (m)	mean height (m)	footprint (10^6 m^2)
Average regular nourishment	2,4	600	4000	~300	~2.0	1,2
Sand Motor	21,5	10.750	2000	~650	~16,5	1,3

Table 1. Order-of-magnitude estimates of the footprint area of a mega-nourishment and an equivalent volume of regular shoreface nourishments (regular nourishments data from Rijkswaterstaat, Kustlijnkaarten 2019, period 2009-2018

All in all, the operational objective of maintaining enough sand in the coastal profile is met over a gradually expanding stretch of coast, as well as the additional operational objective of nature-driven distribution alongshore.

Little of the nourished sediment is lost from the coastal system, but not all of it is found back on the upper shoreface. This suggests that also the lower shoreface (the foundation) benefits. In that sense, the project has proven to be successful as an experiment and a showcase.

The Sand Motor experiment has also shown that a slightly different design may help to materialise the envisaged additional benefits (Luijendijk and Van Oudenhove, 2019):

- the rate of ecosystem recovery strongly depends on the sediment composition; if it is the same as before the nourishment, recovery is rather fast; in case of a different composition it takes much longer;
- aeolian transport into the dune area, as well as juvenile dune formation on top of the nourishment, also depends on the composition of the nourished material; shells, clay and coarse sediment may cause armouring of the top layer if not frequently reworked by wave action;
- a shallower lagoon would prevent anoxia of the deeper layers, as has been the case after some time in the lagoon of the Sand Motor; the lagoon would also fill up more rapidly and, with its fertile mud deposits, it would sooner become a green dune area;
- the lake at the Sand Motor tends to trap wind-blown sediment, at the expense of juvenile dune formation in front of the existing dunes;
- the environmental benefits of the hook-shape can be doubted, if it were only because it rapidly evolves to the more natural shape of a gaussian hump and therefore exhibits a very dynamic low biodiverse environment.

Finally, expectations among stakeholders and the public should be managed by careful framing of this type of high-exposure projects.

Step 5: Overarching objectives met?

Given this experience, are mega-nourishments the best method to maintain the North Sea coast if 40-85 million m^3 of sand is needed per year (Delta Committee, 2008)? In an analysis, ‘before the fact’, Mulder et al (2007) conclude on the basis of a numerical model study looking 150 years ahead that:

- repeated nourishments high on the profile (i.e. the beach or the upper shoreface) are effective in keeping the coastline in place (operational objective), but insufficiently compensate coastal retreat at deeper water; the resulting steepening of the profile leads to an increasing ‘loss’ of sediment to deeper water; from the perspective of the second strategic objective, however, this ‘loss’ is rather a gain, though by itself insufficient to maintain the coastal foundation;
- maintaining the coastal foundation along with sea level rise ultimately

reduces coastline retreat; hence a better maintained coastal foundation requires less coastline maintenance in the long run; It can be questioned though whether the reduction of coastline maintenance volumes compensates for the extra sand needed to maintain the coastal foundation. The latter also depends on the exact formulation of the objectives and the definition of the coastal foundation.

- both the coastline and the coastal foundation profit locally – and over a gradually increasing reach – from concentrated nourishments.

Apart from these qualitative conclusions, Table 1 shows that 40 million m^3 per year would mean roughly 16-17 regular nourishments per year, with a total footprint area of 20 106 m^2 and a disturbed coastal length of approximately 67 km. If the whole volume would be realised with mega-nourishments of the size of the Sand Motor, only 2 would be needed per year, with a total footprint area of 2,6 106 m^2 and only 4 km of initially disturbed length. Although a comparison of these numbers is probably not fair, they do illustrate the need to prepare for a different nourishment practice utilising larger nourishments.

To what extent the benefit/cost ratio of mega-nourishments is higher than that of smaller-scale traditional nourishments depends on the perspective taken. From the point of view of the short-term operational objective of keeping the coastline in place, traditional nourishments may be more cost-effective (immediate return on investment in terms of sand on the coast). Yet, the economy of scale works in favour of large nourishments. Mobilisation and demobilisation costs are less, as are operational costs, as larger trailing suction hopper dredges can be employed, and less sediment has to be pumped onshore. Van der Bilt (2019) showed for a regular nourishment project that approximately 60% of the total CO_2-emissions were associated with pumped unloading. Avoiding this significantly reduces the energy expenditure and the CO_2-footprint. Note that changing the preferred nourishment strategy (two 20-million m^3 nourishments per year, instead of twenty 2-million m^3 nourishments) demands a thorough revision of the present-day planning strategy for coastline maintenance.

When taking a strategic, long-term perspective, the additional physical, societal and environmental benefits of mega-nourishments may help turn the balance (Oost et al., 2016; Brown et al., 2016). To what extent this is indeed the case depends on the local conditions: not every location is suitable along a coast with so many vested interests and so much infrastructure (beach resorts, harbours, marinas, outfalls, landfalls, etc.).

Step 6: Governance context

The Netherlands government has a clear coastal maintenance policy in place, with well-defined strategic and operational objectives at the scale of the Dutch coast. Prevailing laws and regulations explicitly support the policy of dynamically preserving the coastline with the BKL as a reference, but this is not (yet) the case for the coastal foundation. Hence beach and foreshore nourishments have a legal basis and can be enforced, but other types of nourishments, like concentrated mega-nourishment, can be challenged by opponents claiming negative effects. This means that at present, mega-nourishments on the North Sea coast require consensus of many stakeholders, which clearly reduces the agility of mega-nourishments as a method of large-scale coastal maintenance. On the other hand, positive side-effects of mega-nourishments increase the number of potentially supportive stakeholders, hence the possibilities for finding additional funding sources.

With the lessons learned from the Sand Motor experiment, application of multiple mega-nourishments seems technically and ecologically feasible, though possibly complicated by the involvement of many stakeholders and vested interests.

Eco-enhanced scour protection (marine, hard, biotic)

Step 1: Strategic and operational objectives and breakdown of the realisation scheme

The North Sea is rich in marine resources including fisheries, aggregates (sand and gravel), oil and gas. It is one of the most productive seas in the world, with a wide range of plankton, fish, seabirds and benthic communities. The area contains some of the world's most important fishing grounds. The deeper northern regions of the North Sea have a higher diversity and less biomass than the shallower southern regions. Many human activities have an impact on the biodiversity of the North Sea. The marine ecosystems are under intense pressure from fishing, fish farming, seaweed farming, invading species, nutrient input, recreational use, habitat loss and climate changes; most notable are the effects of fisheries and eutrophication. As a result, the whole marine ecosystem in the North Sea is deteriorating. Similar trends are observed in many shelf seas around the world, caused by intensifying exploitation, eutrophication and pollution. (see, for instance, http://www.coastalwiki.org/wiki/Biodiversity_in_the_European_Seas#_note-North_Sea, http://reports.eea.europa.eu/report_2002_0524_154909/en).

Offshore wind farms play an important role in the transition to sustainable energy and much effort and money are spent to develop them. This raises the question to what extent these efforts can be directed to the benefit of ecosystem restoration. Commercial fisheries are not allowed in wind farms in the Netherlands sector of the North Sea (Staatscourant, 2018), but this only provides potential shelter and breeding ground to species that easily migrate, such as fish. Less mobile species, such as crustaceans, reef building worms and shellfish, once removed from the area, do not easily come back via re-colonisation, by lack of larvae sources, favourable biophysical or biochemical feedbacks, and specific habitats.

Recently, the Netherlands Government added an extra requirement to tenders for new wind farms in the North Sea: 'to *make demonstrable efforts to design and build the wind farm in such a way that it actively enhances the sea's ecosystem, helping to foster conservation efforts and goals relating to sustainable use of species and habitats that occur naturally in the Netherlands'* (Regulation 2.15, Netherlands Enterprise Agency, 2018). This nature-inclusive design requirement stimulates engineering consultants and contractors to look for eco-enhancing scour protection methods. It illustrates the government's additional *strategic objective* to rehabilitate the North Sea ecosystem and make wind farms contribute to it through eco-enhancing measures (*operational objective*).

In the framework of the overarching strategy towards renewable energy, the government has designated a number of areas in the North Sea for wind farming (*figure 3*).

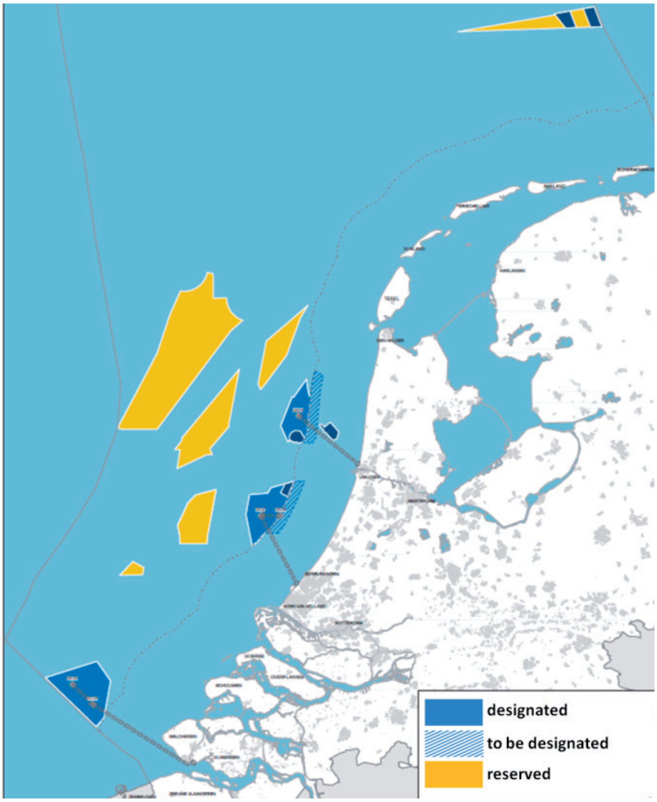

Figure 3. Designated wind park areas in the Dutch part of the North Sea

Realisation of these wind parks, however, is left to the market, so there is no all-encompassing realisation scheme consisting of envisaged individual wind park projects. Moreover, the open formulation of the above requirement does not enforce a coherent overarching realization scheme of eco-enhancing measures. Therefore, we will focus on the scalability of a single class of measures, viz. providing suitable hard substrate.

Step 2: Strategic and operational objectives per wind farm project

Apart from the obvious objective to produce a certain amount of wind energy, the government has introduced an additional *strategic objective*, namely the requirement to contribute to local ecosystem rehabilitation. This can be realized by creating habitat for a number of designated species (*operational objective*).

Depending on the situation, waves and currents may necessitate the seabed around the substructure (mostly monopiles) to be protected against scour, usually by a rock filter (*figure 4*). The design of these filters used to be based exclusively on technical and financial grounds, but in light of the 2018 requirement it has become attractive to explore how they can contribute to ecosystem rehabilitation.

Figure 4. Scour protection around monopiles: opportunity for habitat creation? (source: Van Oord)

Step 3: Project performance

There are basically three methods to ecologically enhance wind farms (Groen, 2019):

1. Habitat creation or enhancement, such that it is more suitable for a number of target species. Scour protection designs can be adapted to achieve this, but also specially designed elements placed in the space between the monopiles (hard substrate, rock mounds, etc.).
2. Stock enhancement, which aims at increasing the abundance of less mobile target species by introducing individuals (larvae, juveniles, adults) that have been reared or cultivated elsewhere. This new stock should be large enough to start a viable and self-sustaining colony within the wind farm.
3. Food enhancement, which aims at increasing the amount of food available for the target species. This may involve additional habitat creation and stock enhancement for the food or prey species.

Table 2 gives a suitability index of wind farms for a number of representative species as a function of the degree of eco-enhancement.

	NS	WF + SP	WF + ESP	WF + SP + SE	WF + ESP + SE
Atlantic cod	2	4	5	4	5
European lobster	1	2	3	2	5
Flat oyster	0	2	3	3	5
Ross worm	1	3	4	3	4
Total	4	11	15	12	19

Table 2. Suitability index (0 = very unsuitable, 5 = very suitable) of wind farms (WF) in the North Sea (NS) with a standard scour protection (SP), an enhanced scour protection (ESP) and stock enhancement (SE). Source: Groen (2019).

Focusing on habitat creation for crustaceans and shellfish, eco-enhancement should aim at the creation of shelter or hard substrate. Rock-filter scour protections around monopiles (*figure 4*) provide hard substrate, as well as shelter in the spaces between the rocks. If the top layer of the filter is made coarse enough, this may provide shelter to larger crustaceans, such as lobsters. Also, between the monopiles of a wind farm there is space for habitat creation. Hard substrate combined with spat seeding may help the return of the flat oyster in the North Sea (Kamermans et al, 2018). Offshore mussel cultures, once economically attractive, are expected to help enrich the marine ecosystem (Van den Burg et al., 2017). Even though fishing within them is not allowed, wind farms may function as breeding, seeding and nursery grounds for the surrounding sea, thus contributing to the stock for fisheries there.

From an ecological perspective boundary conditions are relevant. Therefore, the potential to optimise the ecological value of a windfarm depends on the location in the ecosystem. Factors such as depth and typology of the seabed, hydrodynamics of waves and currents, distance from coasts and river mouths that govern availability of nutrient and light, suspended sediment concentration and sediment transport, and characteristics of the surrounding ecosystem will determine the type of species communities that can establish successfully within the wind farm.

Groen (2019) analysed for a number of species the potential contribution of the Gemini wind farm, a 600 MW wind park in the North Sea north of Groningen, consisting of two plots of 75 monopile-based turbines. Apart from modifying the rock-filters with a coarser armour layer, he added rock piles, concrete tubes and shell-filled nets in the remaining space. Moreover, he imported lobsters and oysters as stock enhancement. *Table* 2 gives an overview of indicative costs and estimated effects. It shows that significant stock increases can be achieved, but at significant extra costs, especially of the coarser armour layer and the adaptation of the filter it necessitates. Note, however, that these extra costs are minor as compared with total costs of the wind park.

Food enhancement will partly be natural, because the seabed is no longer disturbed and mobile species will re-colonize the area. A man-made contribution could be to discard by-catch from passing fishing vessels, but this is by no means sufficient enough and, at the moment, this is against prevailing regulations (in the EU by-catch has to be landed). So far, monitoring of ecological post-implementation project performance is not enforced by wind farm regulations from the Netherlands Government. This will hamper assessment of project performance from a nature-inclusive design perspective, hence feedback of experience onto new projects.

		Original design	**Enhanced design**
Costs (1000 US$)	Filter	1995	2888 - 4115
	Armour	2095	2851
	Rock piles	-	68
	Concrete tubes	-	184
	Shell-filled nets	-	153
	Lobster stock enhancement	-	288
	Oyster stock enhancement	-	955
	Total	**4090**	**7387-8614**
Effects	Estimated number of codfish	1,500 - 93,000	3,000 - 240,000
	Estimated number of lobsters	< 1,000	2,000 - 36,000
	Estimated number of oysters	< 1,000	> 20,000
	Estimated area covered by Ross worm	15,000 m^2	22,000 m^2

Table 3. Indicative costs and effects of eco-enhancing the design of the 150 monopile 600 MW Gemini wind farm. Source: Groen (2019)

Step 4: Objectives met?

In the example shown, the strategic objective of contributing to ecological enhancement will probably be met. Since concrete operational objectives have not been defined, it is not possible to establish the extent to which they are met. Since the effects are estimates based on ecological knowledge gleaned from other locations and other substrates, and there is an influence of the local boundary conditions on what habitats will be established, there is uncertainty how much of the estimates will be (partly) achieved in reality.

Step 5: Overall strategic and operational objective(s) met by the scheme as a whole?

As long as there are neither quantified objectives, nor a coherent realisation scheme, this question cannot be be answered. Yet, the potential effects of a single 0.6 GW wind park (Table 3, bottom part), combined with the ambition of realising as much as 11.5 GW wind energy production on the Dutch Continental Shelf of the North Sea by 2030 (also see Figure 3), gives the hope that there is potential of a significant degree of larger-scale ecosystem rehabilitation. It can be envisaged that the large scale and wide distribution of offshore wind farms will act as stepping stones for species to re-colonise large parts of the North Sea. This needs to be supported by an overarching policy framework that sets clear ecological goals, that allows a translation into operational objectives, otherwise well-meant initiatives per wind park are bound to be wide ranging in technical solutions, and suboptimal or ineffective at the larger scale.

Step 6: Governance context

In order for this rehabilitation potential to materialise, co-ordination between wind park developments now and in the future is necessary. This requires an overarching ecological restoration strategy, setting targets for biodiversity and ecosystem dynamics and resilience. This must be supported by national or international legislation enabling the implementation of this strategy. In that regard, the aforementioned requirement of the Ministry of Economic Affairs (2018), though not objectifiable enough, can be considered as a sign of political will.

3. Other cases

The applicability of the BwN philosophy, and the need to consider the upscaling potential of individual projects, is much wider than the two examples described above. Environments in which BwN has been applied range from marine, via coastal and estuarine, to riverine and inland lacustrine. The infrastructure development may involve abiotic interventions (sand, mud, rock) intended to enhance the ecosystem, biotic ones (seeds, larvae, vegetation, biobuilders) meant to aid or replace hard engineering structures, or mixtures of the two (see Table 4 for a number of examples).

Environment	Abiotic	Mixed	Biotic
Marine	Landscaped sand extraction sites (de Jong et al., 2015)	Eco-enhanced scour protection (Lengkeek et al., 2017)	Coral rehabilitation (Doropoulos et al., 2019)
	Increase speed of habitat recovery by depth variation	Rehabilitate shelf sea ecosystem by habitat creation	Restore ecosystem by seeding or transplanting coral
Coastal	Sand Motor (Luijendijk & van Oudenhove, 2019)	Mangrove rehabilitation (Winterwerp et al., 2013)	Marrowgrass plantation (McHarg, 1969)
	Reduce effective impact on submarine ecosystem / Create sandy supratidal habitat for pioneers	Restore mangrove-based ecosystem and fish stock	Create conditions for pioneer dune vegetation
Estuarine	Shoal nourishment (van der Werf et al., 2019)	Oyster reefs (Walles et al., 2016)	Spartina introduction (Chen at al., 2008)
	Restore intertidal habitat and bird foraging area	Maintain intertidal habitat / formation of live oyster banks	Maintain intertidal marsh / create habitat for other species
Riverine	Longitudinal training dams (Collas et al., 2017)	Willow forest foreshore (de Vries et al, 2021)	Reedbed creation (Sussex Wildlife Trust, 2013)
	Create more diverse river bed habitat	Restore native vegetation, create wetland habitat	Create habitat for endangered bird species
Lacustrine	Houtribdijk sandy foreshore (Steetzel, 2017)	Marker Wadden (Natuurmonumenten, 2019)	Reedbed creation (Sussex Wildlife Trust, 2013)
	Create sand-rich habitat for lacustrine vegetation	Create bird-paradise / clean up surrounding waters	Create habitat for endangered bird species

Table 4. Examples of ecological objectives (obj.) to which BwN-solutions (case) in different environments contribute

4. Discussion

The cases described herein illustrate that for BwN solutions to achieve their full potential at the system scale, they need to be based on a thorough understanding of the natural system, plausibly embedded in a large-scale strategy, as well as part of a larger scale co-ordinated policy arrangement, supported by corresponding legislation and regulations. Moreover, techniques to quantify the effects of multiple BwN projects at the scale of the ambient biotic and abiotic systems need to be developed or improved and supported, more than at present, by post-project monitoring programs. This will ultimately enable plausible estimates of the regional-scale effects and evaluation against overarching strategic and operational objectives at this scale level.

Since it interacts with the natural system, and is part of the natural system, BwN inherently involves uncertainties as it is subject to natural variability and dynamics. This means that plausible estimates of the effects are the best one can give, exact quantities make no sense. It also means that objectives concerning the ecosystem need to be formulated in approximate terms and should focus on the system's resilience, rather than on numbers of individual species. A way forward could be habitat area mapping (specific for each species community) and habitat quality assessment (considering various kinds of local influence factors and larger-scale factors such as connectivity). They can be the basis for estimating both local and large-scale effects. If climate change comes into play, the rate of change of environmental conditions such as temperature is important. Since the infrastructural projects applying BwN solutions are often designed for many years ahead, climate change scenarios have to be taken into account when considering the long-term effects.

The present analysis focuses mainly on the ecosystem, but other environmental aspects, such as carbon and nitrate emission and sequestration also need to be considered. Greenhouse gas emissions of dredging operations to realise sandy solutions can be optimised, but so far, the costs of emission reduction are often much higher than the value society attributes to it at the emission market. CO2 as well as nitrate are bound by vegetation, but they also stimulate certain species, so the question is whether it is the desired vegetation that survives in the long run. This raises the issue of maintenance of the nature component of BwN solutions in order to keep them functioning. Post-project monitoring is vital to make progress here and allow future improvement to such BwN designs.

5. Conclusion

Reality-checking of BwN-solutions for larger-scale applicability requires two perspectives: (1) what is required to realise the large-scale strategic objectives and (2) what is the performance of a single BwN-project in the light of these requirements? The Frame of Reference method offers a systematic way to evaluate BwN-solutions from these two perspectives.

The cases considered herein make clear that plausible quantification of effects and evaluation of effectiveness are only possible if objectives have been formulated in quantifiable terms. They also show that effectively applying multiple BwN-solutions at a regional scale requires a well-defined overarching strategy and legislation directing realisation. In many cases, both are still lacking.

Yet, it has become clear that many BwN-solutions have a distinct up-scaling potential for many types of ecosystems. It is evident that post-implementation monitoring is scarce, hampering the iterative process of the FoR and therefore the degree of learning from realised innovations. Mainstreaming BwN clearly requires more work at various fronts and by various parties.

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