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Coastal Engineers Embrace Nature: Characterizing the Metamorphosis in Hydraulic Engineering in Terms of Four Continua

Jill H. Slinger [1,2,*] and Heleen S. I. Vreugdenhil [1,3]

1 Faculty of Technology Policy and Management, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, The Netherlands; heleen.vreugdenhil@deltares.nl
2 Institute for Water Research, Rhodes University, Artillery Road, Grahamstown 6140, South Africa
3 Deltares, Boussinesqweg 1, 2629 HV Delft, The Netherlands
* Correspondence: j.h.slinger@tudelft.nl; Tel.: +31-15-278-8067

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Abstract: Hydraulic engineering infrastructures, such as reservoirs, dikes, breakwaters, and inlet closures, have significantly impacted ecosystem functioning over the last two centuries. Currently, nature-based solutions are receiving increasing attention in hydraulic engineering projects and research programs. However, there is a lack of reflection on the concomitant, fundamental changes occurring in the field of hydraulic engineering, and coastal engineering in particular, and what this could mean for sustainability. In this article, we signal the shift from conventional to ecosystem-based hydraulic engineering design and characterize this in terms of four continua: (i) the degree of inclusion of ecological knowledge, (ii) the extent to which the full infrastructural lifecycle is addressed, (iii) the complexity of the actor arena taken into account, and (iv) the resulting form of the infrastructural artefact. We support our arguments with two carefully selected, iconic examples from the Netherlands and indicate how the stretching ideals of ecosystem-based engineering could engender further shifts towards sustainability.

Keywords: ecosystem-based design; Building with Nature; nature-based solutions; infrastructure lifecycle; coastal and river engineering; impacts on nature and society; multi-actor systems; multifunctional flood defense; critical reflection

1. Introduction

Since its inception, hydraulic engineering has focused on the design of infrastructures to serve expressed societal needs within the natural aquatic environment. Traditionally, hydraulic designs focus on controlling or withstanding natural fluctuations to facilitate economic and social development and to create safe living spaces for humans. As such, hydraulic engineers are key enablers of the Anthropocene [1]. For example, dam construction to store water and ensure freshwater supply even under low river flow conditions, building breakwaters to allow safe access to harbors, or designing dikes for flood defense. After two centuries of hydrological modification of many systems across the globe, it is now widely understood that these infrastructures impact the natural regulatory services of ecosystems [2]. In recent years, the wetlands in Louisiana [3], the dunes near New York [4], and the mangrove forests in the Philippines [5] have demonstrated that they too reduce the effects of coastal flooding. The growth in understanding of the natural environment, its benefits for human society [1,2], and the inequity of the expressed societal needs [6] is changing the field of hydraulic engineering. Hydraulic engineers increasingly need to use knowledge about the natural and the social environments in designing hydraulic infrastructures.

It is within this context that concepts like "Building with Nature" [7,8], "Engineering with Nature" [9], "Working with Nature" [10], "ecological engineering" [11], "nature-based flood defenses" [12], "integrating green and gray" [13], and "cyclic floodplain rejuvenation" [14] are emerging. These concepts are rooted in a deep knowledge of the dynamic, abiotic processes acting in the aquatic environment and a respect for the biotic environment. They specifically seek to effectively use natural materials, interactions, and dynamic processes in the design, realization, operation, and maintenance of hydraulic infrastructures. They strive for more ecosystem-based hydraulic engineering while acknowledging social complexity.

However, this begs the following question: "How are these concepts changing hydraulic engineering?" In this article, we apply critical reflection [15] in describing and conceptualizing how the hydraulic engineering design process has changed in recent years as a consequence of the increased understanding of ecosystems and their potential contribution to infrastructure development. Whereas Temmerman et al. [16] primarily ascribe the shift towards ecosystem-based coastal engineering to an increase in global environmental risks along coasts, we focus on the design process. We characterize the metamorphosis in the field of hydraulic engineering in terms of four continua spanning (i) the degree of inclusion of ecological knowledge, (ii) the extent to which the full infrastructural lifecycle is addressed in the hydraulic engineering design, (iii) the complexity of the actor arena taken into account, and (iv) the resulting form of the infrastructural artefact. We then apply our characterization to two Dutch examples from a range of international cases [8], distinguishing the original conventional hydraulic engineering designs from the new nature-based engineering designs in these examples and so demonstrating how we consider hydraulic engineering is changing. Finally, we call upon hydraulic engineers to reflect critically on the phenomenon of ecosystem-based design in their field and on our characterization of its metamorphosing effects. Is the metamorphosis we have conceptualized and the insights on design practice going to lead to lasting change? What actions are required to embed the metamorphosis in design practice?

2. Methods

As policy scientists working closely with coastal and river engineers from 2013 onwards, we employed the method of critical reflection (Figure 1), which, through reflection about action, seeks to initiate reflection for action [15,17]. According to Fook [17], critical reflection can free us from restrictive ways of knowing and indicate potential avenues for change. Indeed, Morley [18] claims that critical reflection allows us to research ways to promote congruence between practice-based aims and the ways we actually engage in practice.

Figure 1. The method of critical reflection employed in this study.

Therefore, to initiate broader awareness of the changes in design practice amongst engineers, we first engaged in a process of deconstructive and subsequent reconstructive discussions (Appendix A), gradually formalizing our observations of the changes in engineering design practice (the action) as a metamorphosis in hydraulic engineering. This conceptualization has, as its basis, the experiences of the broad Dutch and allied international network of civil engineers who contributed substantive content to the series of activities listed in Table A1 of Appendix A. The range of participants and the agenda of the activities were often not under the control of the authors. Instead, the deconstructive and reconstructive processes listed under the individual activities in Table A1 were mostly undertaken as a single agenda item within a broader workshop or conference activity with opportunities for more personal engagement and feedback provided in each instance. Deconstructive processes involved questions on why choices were made or steps taken in an engineering design process, whereas reconstructive processes involved presenting partial explanations to diverse audiences and receiving correction and feedback. The conceptualization of a metamorphosis in hydraulic engineering in terms of four continua forms the first result of this critical reflection process.

Next, we selected two recent Building with Nature examples from a range of international projects in the EcoShape database [8] and in the Massive Open Online Course Engineering: Building with Nature 1x, in which over 20,000 professionals (primarily engineers) from 168 lands participated from 2016 to 2020 (www.edx.org). The iconic status of the examples from the coasts of South and North Holland [19,20] was important in their selection, as was the availability of publicly available information on the preceding, more conventional engineering infrastructures and the new infrastructures (e.g., https://www.rijkswaterstaat.nl/kaarten/kustlijnkaart.aspx and https://www.dezandmotor.nl/en/). The information allowed us to analyze the changes from conventional towards nature-based infrastructural design in terms of our four continuum conceptualization. This analysis and its visualization form the second result of our critical reflection process.

Finally, through this publication, we seek to advance the critical reflection process further and engender an active response on the part of engineers (reflection for action) [17,18]. We call upon them to apply this conceptualization to characterize new hydraulic engineering designs in terms of the four continua so that shifts in design practice become apparent.

3. Results: The Four Continuum Characterization

The output of an engineering design process is a design artefact, and it is the changing form of hydraulic engineering artefacts that has received the most attention from proponents of nature-based solutions [7–12]. However, our focus on the design process itself in addition to its product, the designed artefact, allowed us to distinguish four continua spanning (i) the degree of inclusion of ecological knowledge, (ii) the extent to which the full infrastructural lifecycle is addressed in the hydraulic engineering design, (iii) the complexity of the actor arena taken into account, and (iv) the resulting form of the infrastructural artefact. Although the continua are not fully independent of each other, for instance, the inclusion of more ecological knowledge in the design process is likely to result in a more nature-based artefact, they do reflect the design process and its product more fully.

3.1. Fields of Knowledge

First, we identified a change in the type of knowledge used in the design of the hydraulic engineering infrastructure. In contrast to traditional hydraulic engineering, nature-based hydraulic engineering requires the application of both ecological and engineering knowledge. Assessing the type of knowledge applied and the degree to which it is used is complex. Here, we adopted nine engineering design principles [21] and 11 ecological design principles [22] to assess the interdisciplinarity of the design. The trade-offs made in the character and functioning of the ambient natural environment to achieve the functional requirements of the hydraulic infrastructure are explicated in terms of these design principles, revealing the degree to which knowledge of the intrinsic character and functioning of the ecosystem is utilized in the engineering design process. This continuum therefore extends from only using hydraulic engineering knowledge, which includes geotechnical knowledge, to the full use of both the ecological and hydraulic engineering fields of knowledge, i.e., ecosystem-based engineering.

This continuum is depicted as extending from a single strand or field of knowledge on the left towards an interwoven multiplicity of knowledge fields on the right in the two uppermost tessellations of Figure 2.

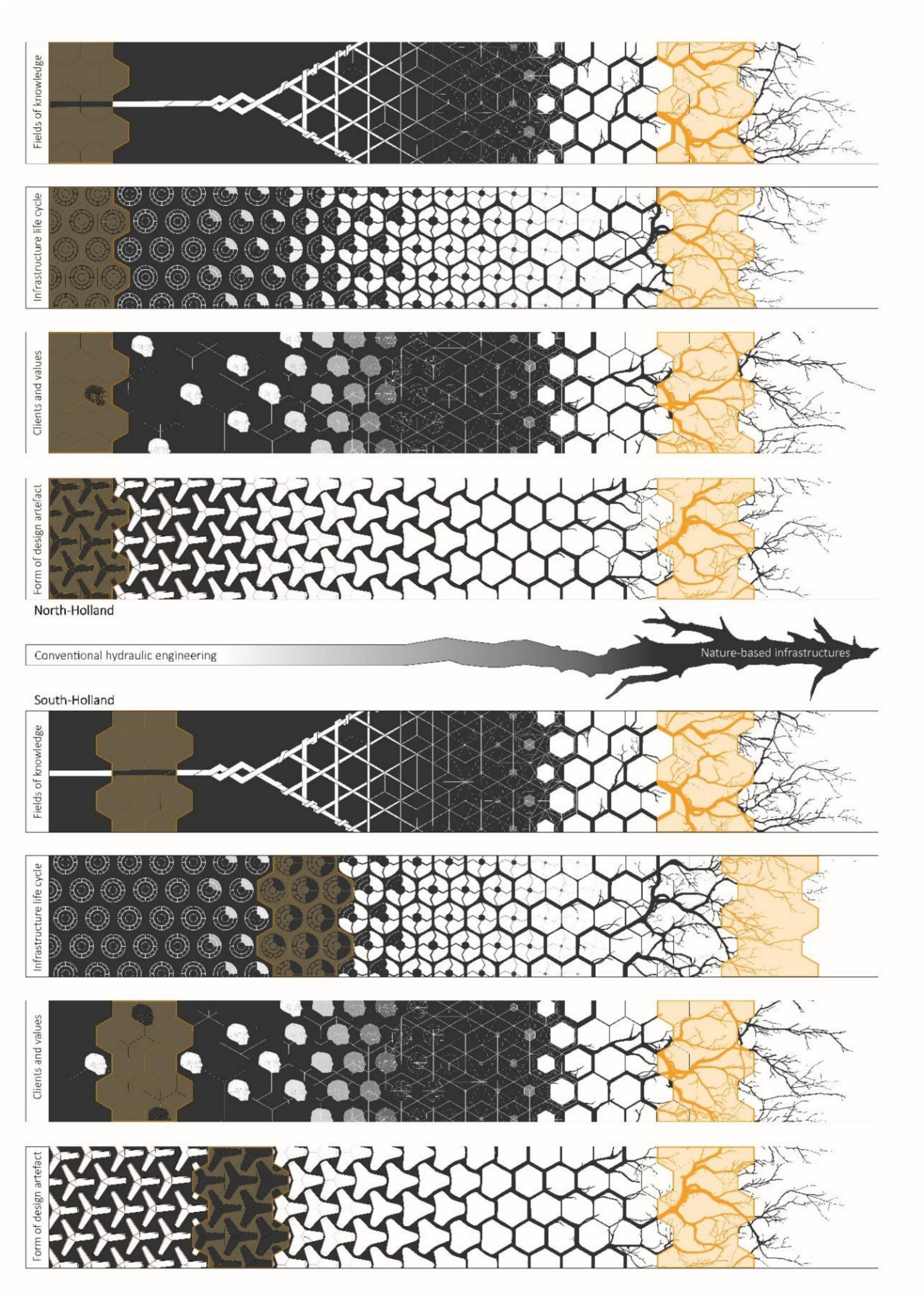

Figure 2. The metamorphosis in hydraulic engineering represented by the two examples of old infrastructures (brown) and new infrastructures (yellow) on the coasts of North Holland (**top**) and South Holland (**bottom**). The degree of adoption of a Building with Nature approach is characterized in terms of four continua: (i) fields of knowledge, (ii) infrastructure life cycle, (iii) clients and values, and (iv) form of the design artefact. A shift can be observed from more conventional hydraulic engineering designs marked in brown and located towards the left-hand side to nature-based infrastructures marked in yellow and located towards the right-hand side.

3.2. Phases of the Infrastructure Life Cycle

Second, we observed that in contemporary designs of hydraulic engineering infrastructures, later phases of the lifecycle of an infrastructure are specifically addressed. Therefore, the realization, operation, and maintenance phases are now taken into account in the design phase [23]. This represents an acknowledgement of the long lifetime of most hydraulic infrastructures, their effects in structuring society through their existence, operation, and use [24], and the ecologically based concepts of lifecycle analysis [25]. The degree to which the strategic goals associated with particular design choices are translated into more operational goals for the later phases in the construction and maintenance of an infrastructure have been assessed in a number of instances [26]. Accordingly, this continuum extends from the usual practice of designing for a single phase to designing for the lifetime of an infrastructure and so represents a departure from standard hydraulic design practice.

This continuum is depicted as extending from single-phased design on the left towards increasing inclusion of multiple phases (gradually filled circles) to lifecycle design (completely white circles) on the right of the upper middle tessellations of Figure 2.

3.3. Clients and Values

Third, we distinguished design for multiple actors across multiple values from design for a single client, often a representative of a public organization articulating societal needs. Geopolitical research has revealed that hydraulic infrastructures can serve the elite and not necessarily society as a whole [27,28]. Moreover, the complexity of settings in which many and conflicting stakeholder interests and values co-occur mean that networked solutions and a broader coalition of actors are required for the resolution of these wicked problems [29,30]. In many "Engineering with Nature" and "Building with Nature" projects executed to date, there have been coalitions of private and public actors in new configurations of cost and benefit sharing to ensure that the hydraulic infrastructures deliver increased living quality over their lifetime. This is exemplified in the Sand Motor [31] and the new Hondsbossche Sea Defense [32], in which the provision of high-quality, if temporary, recreational areas in addition to enhanced coastal safety and flexibility in adapting to climate change played a major role in the approval process. This continuum therefore extends from a single client orientation to designing for multiple actors across multiple values.

This continuum is depicted as extending from a single client at the left across an interconnected network of actors (increasing whiteness) to a completely connected multiplicity of actors and their values (complete whiteness) at the right of the two lower middle tessellations of Figure 2.

3.4. The Form of the Design Artefact

Fourth, we distinguished a change in the form of the resulting design artefact: the hydraulic infrastructure. Does the artefact, the outcome of the design process, exhibit attributes of a conventional hydraulic engineering infrastructure? Or does it also exhibit features of ecosystem-based design? Natural processes, interactions, and materials may be incorporated into the design, resulting in a hybrid form, such as a dike-in-dune construction [4], or the infrastructural artefact may comprise entirely of natural material and the design may make use of dynamic ecosystem processes. This continuum therefore extends from a conventional, static hydraulic infrastructure through hybrid infrastructural forms to a fully nature-based, dynamic artefact in the aquatic environment.

This continuum is depicted as extending from a single armor unit that is used in conventional breakwaters on the left through an increasingly abstract form to a completely white and natural image on the right of the lowest two tessellations of Figure 2.

4. Results: Visualizing the Metamorphosis in Hydraulic Engineering for Two Cases

Next, we analyzed two coastal examples from the Netherlands: on the North Holland coast and the South Holland coast. The key characteristics of the old Hondsbossche and Pettermer dike, the oldest sea dike in the Netherlands, are compared with the new sea defense infrastructure on the North Holland coast in Table 1. Likewise, in Table 2, the old sea defense strategy of beach and shoreface nourishment is compared with the innovation of the Sand Motor on the South Holland coast. In the North Holland example, the choice was made to move from a stone dike to an extensive, shallow sandy foreshore and dunes as primary flood protection infrastructure [32]. In the South Holland example, the strategy of regular sand nourishment of the coast was scaled up to that of a once-off mega-nourishment designed to meet flood protection requirements over decades [31].

Table 1. The sea defense on the North Holland coast demonstrating the metamorphosis in hydraulic engineering.

Old Hondsbossche and Pettermer Dike	New Hondsbossche Sea Defense [32]
Following the St. Elizabeth flood of 1421, the first earthen dikes were constructed near Petten.	Between 30 and 35 × 106 m3 sand was deposited on the seaward side of the existing dike in 2015.
In 1823, the dikes at Hondsbossche were rebuilt from stone, forming the first of the modern Dutch dikes.	Design consists of a shallow sandy foreshore and beach connected to a diverse dune habitat, shaped by wind and water over time.
In 1977, the stone dike was reinforced with armor units and raised to meet the safety standards of the time: an inundation risk of 1 in 10,000.	The dynamic dune and beach environment seaward of and covering the old dike is envisaged as a habitat for rare plants, birds, and other animals, supporting biodiversity.
Between 2001 and 2006, the existing dike was deemed a "Weak Link" in the flood defense chain as it would not continue to satisfy flooding safety standards over the next 50 years and so required improvement.	Aims of the new sea defense explicitly include flood protection, recreation, nature development, and knowledge acquisition extending over a period of 10 to 20 years.

Table 2. Beach nourishment on the South Holland coast demonstrating the metamorphosis in hydraulic engineering.

Beach and Shoreface Nourishment (1990–2010)	Sand Motor [31] (2011 Onwards)
Regular nourishments of the beach or shoreface with sand were undertaken at intervals of 3 to 5 years. The location of the nourishments was planned annually at a national level to prevent coastal retreat (maintain a base coastline position).	To combat coastal erosion, 21 × 106 m3 sand was deposited in a hook shape on the shoreface of the coast of South Holland during a single intervention in 2011.
The volume of sand required for a shoreface nourishment was roughly equivalent to that present in nearby underwater sand banks and the effects extended up to 3 km along the coast over the next 3 years. The total volume of sand required for the entire Dutch coast was 12 × 106 m3 in 2011.	Sand is redistributed from the mega-nourishment by tides, waves, and winds towards the beach and dunes along a 17 km stretch of coastline.
The ecosystem had not recovered before the next nourishment occurred, usually within a period of 3 to 5 years.	Project lifetime covers several decades during which the shoreface, beach, and dune habitats are not again disturbed by sand nourishment.
Needs of recreation and ecosystem requirements were taken into account in timing the nourishment (not in summer), but the primary aim was coastal defense.	Aims explicitly include coastal defense, nature, recreation, and education.

To demonstrate the metamorphosis in hydraulic engineering, the old and the new sea defense infrastructures on the North and South Holland coasts were positioned on the four continua. Their positioning on each of the four continua reflects the degree to which elements of a Building with Nature approach have been incorporated in the designs. Conventional hydraulic engineering infrastructures, which have few nature-based elements, are therefore located towards the left-hand side of each of the four continua. For instance, the old Hondsbossche and Pettermer dike, a conventional hydraulic engineering infrastructure, is located on the far left of each of the four continua in the upper part of Figure 2. This is not the case for the beach and shoreface nourishment strategy from 1990 to 2010 on the South Holland coast (lower part of Figure 2). Instead, the use of hydrodynamic and morphological knowledge in designing the shoreface nourishments is indicated by a positioning further from the left boundary in continuum 1, while the cognizance taken of cyclical bar dynamics in choosing shoreface nourishment justifies a position nearer to the middle of continuum 2. Taking account of the needs of beach pavilion owners and recreants regarding the timing of beach nourishments means that the position on continuum 3 is also a little way away from the left boundary. Finally, whereas the form of shoreface nourishments is highly dynamic, that of beach nourishments is less so, explaining why the position on continuum 4 lies between those of continuum 1 and 3 and that of continuum 2.

In contrast, the Sand Motor and the new Hondsbossche Sea Defense are located towards the right-hand side of each continuum, indicating that considerable ecological knowledge in addition to hydraulic engineering knowledge was employed in their design (continuum 1). It is noteworthy that the full lifecycle of the new infrastructure is incorporated in both of the new designs, but with the Sand Motor, it is even designed to disappear over time (continuum 2). The Sand Motor is therefore positioned further to the right than the new Hondsbossche Sea Defense on the second continuum (Figure 2). Aspects of spatial quality and education in addition to nature and engineering values are explicitly addressed, extending the functional requirements for the new infrastructural designs beyond standard hydraulic engineering criteria towards the right-hand side of continuum 3. In terms of the form of the artefact, the old North Holland dike (as static infrastructure) and the local South Holland beach and shoreface nourishments (slightly more dynamic) are located at the left of continuum 4. However, the highly dynamic, nature-based artefacts that now replace them are located towards the right of this continuum.

Inspecting the representation of the old and the new infrastructures on the four continua in Figure 2 allows us to detect at a glance the shifts, or metamorphoses, from conventional hydraulic engineering (on the left) towards nature-based infrastructures (on the right) that have occurred along the North and South Holland coasts.

5. Concluding Discussion

The exact position of an infrastructure on each of the continua cannot be determined unequivocally and will always be subject to debate. However, the value of distinguishing the four continua lies in (i) stimulating discussion amongst hydraulic engineers regarding the degree to which a hydraulic engineering solution can be termed ecosystem-based design and (ii) engendering reflection on this metamorphosis in the field of hydraulic engineering. Such discussions may act to curtail "greenwashing" and can stimulate the field of hydraulic engineering to move from the left-hand side of the continua towards the challenging ideals on the right-hand side of the continua.

Over time, we anticipate that the understanding of what it means to be an ecosystem-based hydraulic infrastructure will alter, and the value attached to ecosystem-based design ideals will increase. It is our conviction that infrastructures that would now score as marginally ecosystem-based design will later be considered as primal and early examples of a new type of sustainability engineering. However, whether hydraulic engineers continue to embrace nature will also depend on their conceptualization of themselves as engineers in the Anthropocene. Will they reflect critically on the phenomenon of ecosystem-based engineering design and their changing role in global sustainability?

We call upon hydraulic engineers to characterize each new Building with Nature/Working with Nature/Engineering with Nature design in terms of the four continua. Such action on the part of hydraulic engineers is a necessary first step in determining whether design practice is indeed changing and will provide a wider information base for reflection and continued learning.

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Conflicts of Interest: The authors declare that they have no financial or other interests that may be considered to influence the opinions expressed in this manuscript, which was prepared within the freedom provided by the academic environment of Delft University of Technology.

Data Availability: The data generated or analyzed during this study are referenced in this published article. Two movies on the engineering design principles and ecological design principles are included as data references 14 and 15 and are freely downloadable in mp4 format. The movies represent original material prepared for educational purposes. Full transcripts of the movies are available on reasonable request to the first author if required.

Appendix A

The appendix contains Table A1 listing the authors' experiences within coastal and river engineering over the period 2013 to 2020, which served as the basis for the critical reflection method applied in this research.

Table A1. Authors' critical reflective experiences with coastal and river engineering over the period 2013 to 2020.

Year	Activity with Critical Reflection Process (in Brackets)	Substantive Content	Participants	Author
2013–2014	Series of discussions (deconstructive)	Perspectives on Building with Nature, whether and how the concept should be incorporated in engineering education.	Hydraulic engineer and ecologists both within and outside the Building with Nature community.	J.S.
2013–2014	Series of discussions (deconstructive)	Potential for multidisciplinary collaboration within the Faculty of Civil Engineering and Geosciences (CiTG), TU Delft.	Thought leaders on the staff of the Faculty of CiTG.	H.V.
2014, 2015	Series of discussions (deconstructive)	Building with Nature concept and how this relates to "Engineering with Nature" and "Working with Nature".	Dr. Ir. Ronald Waterman.	J.S.
26 March 2015	Delft Infrastructures and Mobility Initiative (DIMI) Brainstorm on Building with Nature (deconstructive)	Perceptions of Building with Nature.	Key people from TU Delft and the EcoShape Foundation.	J.S.
8 October 2015	Congress: DIMI on Tour! Building with Nature (deconstructive)	Applications and teaching of Building with Nature.	Primarily engineers, ecologists, consultants, architects, urban planners, and students.	J.S. and H.V.
28 January 2016	DIMI Congress on Deltas and Ports of the Future: towards new synergy of Delta technology, Spatial Design and Governance (reconstructive)	Propositions for discussion on effective implementation and development of the Building with Nature concept and associated governance challenges.	Wide ranging set of participants, including regional policy makers, engineering consultants, urban planners, ecologists, and diverse decision-makers in water, coastal, and environmental domains.	J.S. and H.V.
2017	INTERREG 5B project Building with Nature (reconstructive)	Preparation, presentation, and discussion of business cases for Building with Nature projects, undertaken on behalf of the EcoShape Foundation.	Primarily coastal, water, and environmental authorities of the North Sea countries: Netherlands, Germany, Denmark, Sweden, Belgium, and Scotland	H.V.
2015, 2016, 2017, 2018, 2019	Masters level engineering course Building with Nature in Hydraulic Engineering (deconstructive and reconstructive phases)	Campus-based, blended education on designing Building with Nature solutions using case studies.	CiTG students from TU Delft.	J.S. and H.V.
2016, 2017, 2018, 2020	MOOC Engineering: Building with Nature 1x (deconstructive and reconstructive phases)	Online education on the Building with Nature concept and project examples.	Over 20,000 participants worldwide from a wide range of backgrounds. Primarily engineers, ecologists, and planners.	J.S. and H.V.
2017, 2018	Virtual Exchange Building with Nature (deconstructive and reconstructive phases)	Credit acquiring online education on the Building with Nature concept and project examples.	Engineering, ecology, and planning students from universities in the Netherlands and other countries, e.g., Queensland University, Rice University, University of Leuven, as well as Wageningen University and Twente University.	J.S.

Table A1. *Cont.*

Year	Activity with Critical Reflection Process (in Brackets)	Substantive Content	Participants	Author
2011–2017	NatureCoast research program (deconstructive and reconstructive phases)	Nature-based nourishment of coastal systems.	Primarily civil engineering, ecology, and policy researchers. Public policy organizations, consultants, funders, and societal organizations also participated.	J.S.
2015–2020	CoCoChannel research project (deconstructive and reconstructive phases)	Co-designing coasts using natural channel–shoal dynamics.	Primarily civil engineering, ecology, and policy researchers. Public policy organizations, consultants, and funders also participated.	J.S.
2016–2020	Sustainable Ports in Africa research project (deconstructive and reconstructive phases)	Applying Building with Nature concepts in the integrated design of port developments for enhanced sustainability.	Coastal engineers, ecologists, economists, and policy analysts. Wide range of supporting parties, such as harbor authorities in the Netherlands and Africa, port logistics and operational companies, engineering consultants, dredging companies, societal and environmental organizations, and financiers.	J.S. and H.V.
2016	Workshop: The Sand Motor, 5 years of Building with Nature (reconstructive)	Participatory international reflection on the (success of) Building with Nature concept and how this relates to "Engineering with Nature".	Invited international delegates included renowned ecologists and engineering scientists as well as acknowledged leaders of the "Engineering with Nature" concept. The majority of attendees were engineers, scientists, and ecologists.	J.S. and H.V.
2019	BeSafe research program (initiated 2015) (reconstructive)	Decision-making for nature-based solutions to flood defense.	Primarily civil engineering, ecology, and policy researchers. Public policy organizations, consultants, and funders also participated.	H.V. and J.S.
2 November 2017	PIANC NL meeting (reconstructive)	Building with Nature application to ports in Africa and elsewhere and how this relates to "Working with Nature".	Mainly engineering consultants, harbor authorities, and some scientists.	J.S.
May 2018	PIANC World Congress (reconstructive)	International applicability of Building with Nature concepts to ports and harbors, relationship to "Working with Nature" and "Engineering with Nature", governance challenges.	Wide range of international participants, primarily port and harbor engineers and scientists but including international trade and diplomatic delegates.	J.S.
2020	Beyond Engineering: Building with Nature 2x (reconstructive)	Online education on the social context of the Building with Nature concept, including project examples.	Over 800 engineers, ecologists, and planners as participants.	J.S. and H.V.

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