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Cover page

This deliverable documents developing and realizing a novel hybrid eco-dike prototype designed under Work Package 15 of the DuneFront project. This work aims to integrate bioreceptive cement materials and a digitally fabricated geometry into a scalable coastal defense element that balances hydraulic performance with ecological functionality.

The final prototype consists of a modular, 3D-printed octagonal unit with embedded cavities, sloped planes, and interlocking edges. Internally, the structure includes a central star-shaped core and a twisted sinusoidal surface geometry, both designed to enhance ecological colonization, moisture retention, and mechanical bonding with an infill of self-compacting concrete (SCC). The outer shell is fabricated using mortar-based bioreceptive mixes developed in D15.1, while SCC casting provides the necessary structural robustness.

Robotic 3D printing using an ABB IRB 6600 robotic arm will be employed to construct the prototype at lab scale, following a layer-by-layer, inside-out printing strategy. The full-scale implementation is planned at a test site in De Panne, Belgium, where the prototype will be installed on a 30° dune slope and compared against traditional revetments and commercial alternatives. The surface features and material composition are optimized to support dune vegetation such as *Ammophila arenaria*, trap sediment, and blend with the local landscape.

This report outlines the design rationale, fabrication strategy, material integration, and implementation plan. It represents a key milestone in translating material and ecological research into deployable, nature-based infrastructure aligned with EU climate adaptation and biodiversity goals.

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Abbreviation	Explanation
D	Deliverable
WP	Work Package
SCC	Self-compacting concrete

1. Overview

1.1 Introduction

1.1.1 Overview of work package 15 (WP15- Co-creation of a new eco-dike prototype)

WP15 aims to design and implement an eco-dike prototype that integrates nature-based solutions with hard infrastructure. The key focus is on creating a biodiverse, resilient, and aesthetically appealing structure through innovative materials and stakeholder-driven processes.

1.1.2 Tasks of Work Package 15

The first major task within WP15 is the development of bioreceptive cement (Task 15.1). This involves creating cementitious materials with optimized properties, such as low pH, increased porosity, and enhanced surface roughness to support biological growth. Various mixtures, including magnesium phosphate cement and bone ash, are being evaluated for their bioreceptivity, structural integrity, and suitability for 3D printing. The goal is to ensure the material is functional and conducive to foster biodiversity on the eco-dike's surface.

Another critical aspect is the realization of complex geometries for eco-dikes through the 3D printing technology (task 15.2). This task focuses on designing shapes that enhance resilience and biodiversity by enabling wind-driven sand trapping and supporting the establishment of vegetation. These geometries will also improve the structure's visual appeal, aligning ecological functionality with aesthetic considerations.

Stakeholder co-creation is significant in WP15 (task 15.3), emphasizing collaborative engagement with local stakeholders to shape the project. This involves multiple co-creation sessions to gather input on design priorities, ecological goals, and the overall vision for the project areas. The process ensures that the eco-dike aligns with local needs, addressing social, ecological, and aesthetic concerns.

Finally, the WP includes the preliminary design and implementation of the eco-dike prototype (15.4). This involves developing technical designs, securing permits, and planning the construction, monitoring, and maintenance of the structure. These steps aim to ensure that the final prototype is not only technically and ecologically viable but also ready for practical application in coastal defense.

1.2 Aims and objectives of this report

This deliverable documents the realization of a novel hybrid eco-dike prototype that integrates bioreceptive cementitious materials developed in D15.1 with a geometry designed to enhance ecological and coastal resilience. Following extensive lab testing of biologically supportive cement mixtures, D15.2 will demonstrate how these materials were used to construct a full-scale or pilot-scale dike segment. The focus is on the structure's shape and materialization, leveraging 3D-printed or modular geometries designed to support biodiversity, wind-driven sand capture, and aesthetic integration into the coastal landscape. The deliverable includes visual and technical documentation of the construction process, from site preparation to final installation, and outlines the planned performance monitoring and ecological integration strategies to be addressed in the following phase (D15.3). D15.2 serves as a bridge between laboratory research (D15.1) and long-term evaluation (D15.3), offering concrete insights into how innovative, nature-based construction materials and forms can be translated into practical, scalable coastal defense solutions.

2. Prototype Design Translation

The prototype eco-dike design developed in WP15 was guided by functional and technical requirements and deeply informed by inspirational references from engineering innovations and natural systems. As part of the design translation process, the team carefully examined a range of existing coastal protection technologies, 3D-printed marine enhancement structures, and biological organisms known for their structural resilience, environmental adaptability, and biodiversity support.

The objective was to develop a hybrid solution combining traditional coastal armor units' wave attenuation, structural strength, and modular logic with the ecological potential, visual integration, and biomimicry observed in marine habitats. Rather than replicating existing shapes, the prototype borrows and reinterprets form principles, void structures, and surface features from these inspirations to create a design that performs hydraulically while inviting ecological colonization, promoting sediment capture, and maintaining aesthetically pleasing integration into the coastal landscape.

These sources of inspiration were selected not only for their proven performance in real-world applications but also for their alignment with the goals of DuneFront: to deliver innovative, nature-based, and scalable protective solutions that enhance biodiversity, involve local stakeholders, and reduce environmental impact. They were discussed, refined, and validated through iterative design workshops and consultations within the project team, and further shaped by the outcomes of Task 15.1.

The design that emerged, centered around an octagonal, porous, interlocking concrete element with sculpted cavities and bio-receptive texture, and is the result of synthesizing ideas from multiple sources into a single, coherent, constructible, ecologically functional geometry.

2.1 Sources of inspiration

The design of the hybrid eco-dike prototype is the result of an interdisciplinary process. It draws on existing engineering solutions and natural systems to optimize hydraulic performance and ecological integration. Below is a detailed overview of the primary sources of inspiration.

2.1.1 Living seawalls

The Living Seawalls project was developed by the Sydney Institute of Marine Science (SIMS) in collaboration with Volvo and other partners. Now being installed in various Australian ports, these seawalls use panels cast in molds that were 3D-printed with biomimetic textures to retrofit traditional flat concrete seawalls, promoting marine biodiversity in urban coastal zones (Figure 1) [1].

The Living Seawalls initiative is rooted in the idea that infrastructure can be designed to function as habitat, not just as physical protection. Their panels mimic the crevices, pools, and surface roughness of natural rock outcrops to encourage the settlement of marine life such as oysters, barnacles, mussels, seaweeds, and fish. The project has shown measurable increases in species richness and abundance, demonstrating the value of surface design in enhancing ecological performance.

Figure 1: Living Seawalls [1]

2.1.2 HARO Block

A key inspiration for the structural and hydraulic logic of the eco-dike prototype is the HARO block, a hollow armor unit developed through research at Ghent University (UGent) in Belgium. The HARO block (Hollow Armor Unit) (Figure 2) was designed to improve the efficiency of coastal protection structures such as breakwaters, by combining structural robustness with significant material savings and enhanced hydraulic performance [2].

The HARO block's defining feature is its high porosity, with up to 51% of its volume consisting of voids. This structure allows it to dissipate wave energy internally rather than merely deflecting it, reducing reflection, overtopping, and scour. The design promotes stability under wave loading and allows for easier handling and installation due to its lighter weight compared to fully solid units.

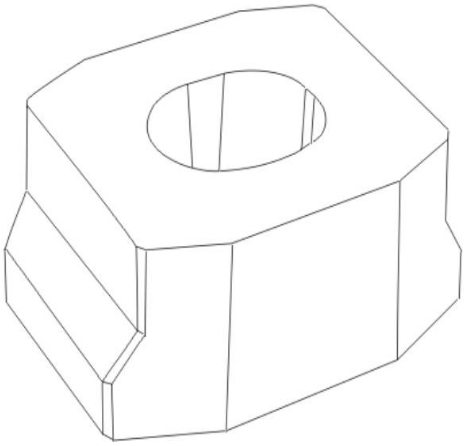

Figure 2: HARO Block [2]

2.1.3 ArmorLoc

The ArmorLoc system, developed by Contech Engineered Solutions, is a widely used interlocking concrete block system designed for erosion control and shoreline protection (Figure 3). Its application spans streambanks, embankments, culverts, and low-energy coastal zones, where it delivers reliable hydraulic performance and long-term durability under variable environmental conditions.

What distinguishes ArmorLoc from traditional hard Armor systems is its open-cell, modular structure that enables both interlocking stability and ecological compatibility. The blocks are designed to conform to natural terrain and resist displacement. At the same time, the open spaces between units allow for vegetation growth and water infiltration, reducing runoff and improving environmental integration. Its lightweight, stackable design allows easy manual installation, making it a cost-effective and scalable solution for various protective landscapes.

Figure 3: ArmorLoc [3]

2.1.4 Hill Block

The Hill block (Figure 4) is a patented revetment block system developed in the Netherlands. It was designed to reduce wave energy, protect against scour, and provide interlocking stability along dikes and embankments. Its widespread use in Dutch water defense systems highlights its proven performance in hydraulic efficiency and durability under high-stress coastal conditions. Its angled, sloped surface and interlocking form set the Hill block apart from conventional Armor units. These characteristics allow it to break incoming wave energy gradually, reduce turbulence, and prevent displacement even under intense wave loading. The design minimizes reflection and enhances energy dissipation by promoting laminar flow over a staggered, roughened surface [4].

Figure 4: Hill Block [4]

2.2 Integration into the Eco-dike prototype

The eco-dike prototype integrates various design principles inspired by innovative coastal protection systems and ecological infrastructure, merging them into a unified structure that balances structural performance, ecological function, and modular scalability.

The prototype's core geometry features a modular, interlocking form, enabling flexible assembly across different site conditions and enhancing overall structural stability. This approach draws from existing revetment and Armor systems, emphasizing ease of installation, even in locations with limited access to heavy machinery. Hollow internal volumes serve dual purposes: reducing material use for sustainability and creating pathways that allow wave energy to dissipate, as demonstrated in similar revetment systems such as the Hill block and HARO block [2], [4], decreasing the impact of wave run-up and scour around the structure.

To support biodiversity, the prototype's surface includes textured recesses, cavities, and sloped contours designed to trap moisture, accumulate wind-blown sand, and provide microhabitats for vegetation. These features are informed by nature-based approaches and eco-engineering research, as demonstrated in nature-based infrastructure projects like living seawalls [1], hydraulic infrastructure can also support ecological colonization. In particular, these design choices facilitate the growth of pioneering dune species such as Ammophila arenaria (marram grass) , enhancing dune formation and long-term landscape stability [5].

Additionally, the prototype's geometry promotes laminar flow across its surface, reduces turbulence, and allows sediment to settle naturally, helping to regenerate the surrounding environment. This design rationale is supported by principles observed in eco-engineering literature, where reduced turbulence contributes to sediment deposition and ecological colonization [6], [7]. The combination of angled planes and porous volumes improves its performance in dissipating energy while supporting dynamic interactions with wind, water, and vegetation. Similar porous revetments and textured surfaces in nature-based costal structures have been shown to attenuate wave energy and enhance ecological performance [8].

Finally, the modular and lightweight design ensures it can be manufactured efficiently and deployed with minimal environmental disruption, an approach widely adopted in nature-based and prefabricated coastal infrastructure [9].

2.3 Formwork or 3D printing strategy

The construction strategy for the eco-dike prototype was grounded in advanced research into extrusion-based 3D concrete printing, integrating sustainable material development and structurally sound formwork design. Inspired by ongoing innovations at Ghent University, the selected approach leveraged the flexibility and geometric freedom of 3D printing to fabricate the complex, bio-receptive forms required for ecological enhancement. From Manu Mohan's research [10], the prototype utilized optimized low-CO_2 printable cementitious mixtures incorporating coarse recycled aggregates and alternative binders to reduce environmental impact while ensuring pumpability and buildability. Simultaneously, insights from Michiel Bekaert's work [11] on 3D printed formwork informed the structural and mechanical performance, particularly the interaction between printed shells and infill material, and the influence of shrinkage, bonding, and curing. The prototype was printed layer by layer using a controlled nozzle path to define hollow geometries and textured surfaces, eliminating the need for traditional molds. This approach allowed precise control over cavity placement, wall thickness, and interlocking edges, making the prototype hydraulically efficient, ecologically functional, and feasible to produce with scalable, digitally driven fabrication methods.

This strategy used for the eco-dike prototype follows a hybrid method that combines the geometric freedom of 3D concrete printing with the structural reliability of self-compacting concrete (SCC). The principle behind this method involves 3D printing a hollow outer shell, essentially a customized, permanent formwork, which is then filled with SCC to form the structural core of the element. The SCC mix that will be used is structurally optimized and designed to reduce environmental impact. This includes the incorporation of recycled aggregates and the selection of low-carbon binder formulations where feasible, aligning with the sustainability objectives of the DuneFront project.

The outer shell is printed layer by layer using a mortar-based 3D printable mix, developed in Task D15.1, that sets quickly enough to support subsequent layers without collapsing. This shell defines the prototype's geometry, surface texture, and ecological features (such as cavities and planter recesses), while acting as a mold for the structural infill.

Figure 5: An example of 3D printing of an outer shell [10]

Self-compacting concrete (SCC) is a highly flowable, non-segregating concrete that can spread into formwork and fill intricate molds under its own weight, without the need for mechanical vibration. Its exceptional workability makes it ideal for applications involving complex geometries, dense reinforcement, or delicate formwork, such as 3D printed shells. In the eco-dike prototype, SCC was chosen to fill the printed outer shell because of its ability to conform to internal voids and ensure complete consolidation without disturbing the formwork. Using SCC improves construction efficiency and ensures high surface quality, uniform strength distribution, and enhanced durability. Moreover, SCC's fluidity helps prevent voids or honeycombing in critical structural zones, making it particularly suitable for hybrid systems where precise internal filling is essential to the performance and longevity of the element.

This two-phase process offers multiple benefits:

- It combines architectural freedom with engineering robustness.
- It allows the printed concrete to focus on form and ecology, while the SCC meeting a target density of 2400kg/m3, delivers the required mechanical performance.
- It enables faster production and material efficiency since the printed material is not designed to carry full structural loads.

This principle, validated by Michiel Bekaert's and others' research, helps overcome industry resistance by retaining the trustworthiness of conventional cast concrete while introducing digital fabrication advantages. It makes it an ideal technique for nature-based infrastructure elements like the eco-dike.

2.4 Modular vs. Monolithic construction decision

In construction, two contrasting approaches often guide structural design: monolithic and modular. A monolithic approach involves casting or building a structure as a single, continuous element. This method offers inherent structural continuity and reduced jointing, making it ideal for large-scale infrastructure with high load-bearing requirements. However, monolithic construction can pose challenges in terms of transportability, site adaptability, fabrication complexity, and repair logistics, especially when dealing with intricate geometries or limited-access coastal zones.

By contrast, a modular approach involves creating a system from repetitive, self-contained units that can be fabricated independently and assembled on-site. Modular construction allows for greater flexibility, scalability, and off-site prefabrication. It is particularly well-suited to digital fabrication methods such as 3D concrete printing, where build volume and printer access are limiting factors.

A modular construction strategy was selected for the eco-dike prototype. Each unit is designed as an independent block featuring bio-receptive surfaces, hollow geometries, and interlocking edges, allowing it to connect mechanically with adjacent units. Several key factors drove this decision:

- Digital fabrication constraints, including printer size and layer-based build limits,
- Ease of transportation and assembly in varied coastal environments,
- Site flexibility, enabling adaptation to local topography without redesign,
- Repairability, where individual units can be replaced if damaged,
- And the opportunity to customize units ecologically, for instance by varying cavity depth or planter placement based on site-specific biodiversity needs.

This modular strategy enhances the eco-dike's constructability and resilience and reinforces the project's emphasis on scalable, adaptable, and nature-integrated design.

3. The Final design

The final design of the eco-dike prototype represents the culmination of material development, ecological inspiration, structural experimentation, and stakeholder input carried out under Work Package 15. Building on the insights gained through the bioreceptive cement testing (D15.1), 3D geometry development, and modular construction strategy, the prototype forms an octagonal, interlocking concrete unit with a porous core and sculpted surface features. Designed for both hydraulic performance and ecological integration, the unit includes angled faces, cavities, and planter recesses to promote wave energy dissipation, sediment accumulation, and colonization by dune vegetation such as *Ammophila arenaria* [12]. Its modular nature allows it to be deployed in series, adjusted to site-specific conditions, and easily transported or replaced. The final design was selected for its functional and ecological benefits and its constructability using 3D printing technologies and SCC infill, ensuring alignment with the DuneFront project's vision of scalable, sustainable, and nature-based coastal defense.

3.1 Geometry and structure

The prototype features an octagonal footprint, chosen for its geometric stability and ease of interlocking with adjacent units. The outer shell includes sloped and angled planes, redirecting incoming wave energy and encouraging sand accumulation at the base. Internally, the unit is designed with hollow voids to reduce weight and material use while acting as zones for ecological enhancement and structural infill with self-compacting concrete.

3.1.1 Geometrical description and components

The final eco-dike prototype consists of three custom-designed geometrical components, all 3D-printed concentrically from the inside out and later filled with SCC. This printing sequence—from core to shell—was chosen to optimize robotic toolpath efficiency and nozzle accessibility, ensuring uninterrupted printing and structural stability. The components include:

- Central star-shaped core – provides ecological cavity and weight reduction (a)
- Rotational sinusoidal geometry – integrated into the shell wall to enhance SCC bonding (b)
- Outer octagonal shell – defines footprint and enables modular interlocking (c)

The SCC will be poured only into the annular cavity between the outer octagonal shell (c) and the sinusoidal geometry (b). These two components will not be in direct contact; instead, the SCC serves as a structural core that mechanically bonds the shell and internal geometry, ensuring strength and cohesion throughout the unit. Minor geometric refinements may be introduced during slicing and print path optimization, in collaboration with the robotic printing partner, which will be reported separately as a follow-up or in the next D15.3.

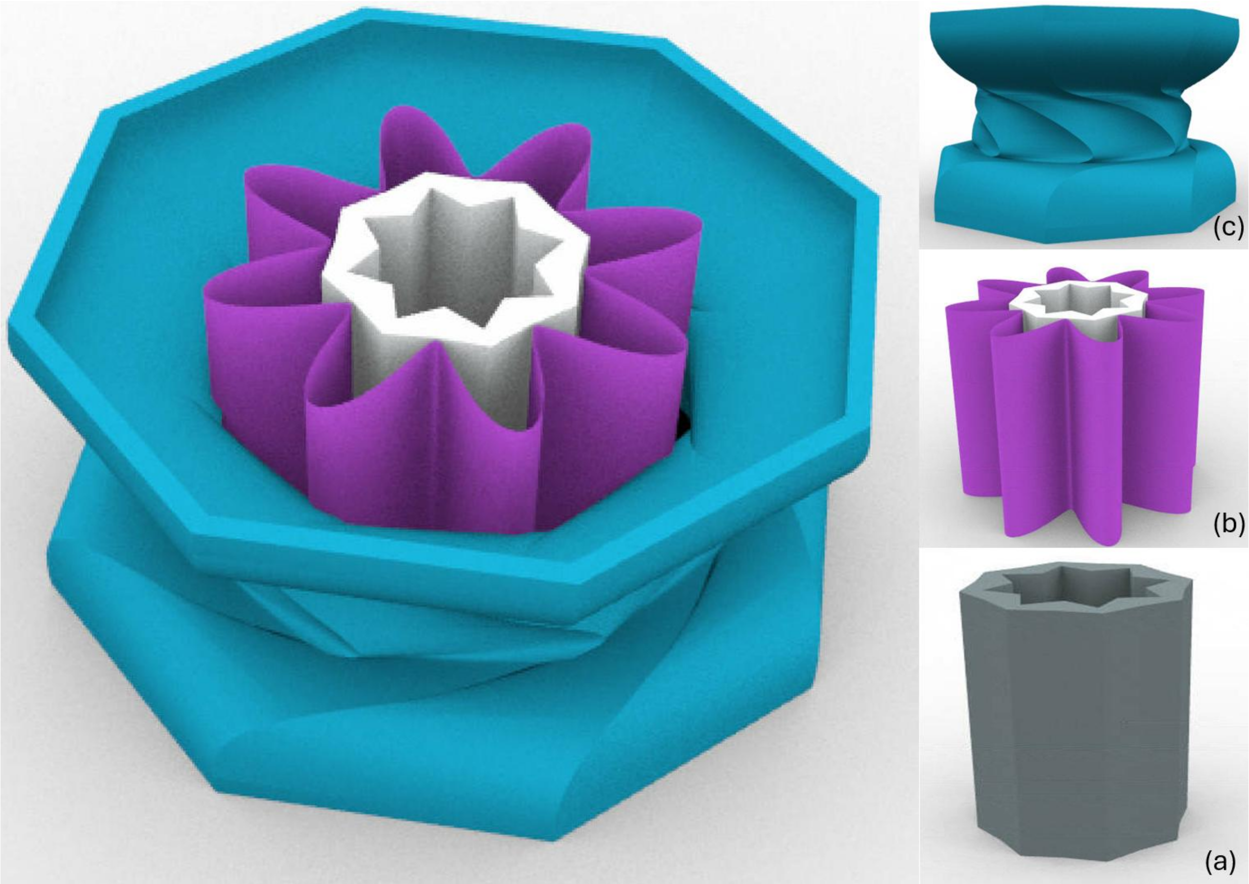

Figure 6: The printed part of the final design

The central star-shaped core is printed first. With its eight-pointed profile, it reduces material volume while increasing internal complexity. The cavity it forms supports moisture retention and ecological colonization, functioning as both a planting pocket and a lightweight structural void.

While initially appearing as a separate component, the rotational sinusoidal geometry is integrated directly into the inner wall of the octagonal shell. It defines the inner boundary of the SCC casting cavity. This twisted, wave-like form is printed concurrently with the shell, streamlining fabrication and ensuring perfect geometric alignment. Though fully embedded and not externally visible after casting, it plays a crucial role in:

- Increasing internal surface area to enhance SCC bonding,
- Acting as a mechanical key to resist delamination and shear stress,
- Enabling a smooth, continuous print path, which reduces toolhead retraction and improves print quality.

The outer octagonal shell, printed last, defines the prototype's external boundary. Its angular geometry allows modular interlocking between adjacent units and supports vertical stacking during site deployment. It also encloses the internal volume and provides the primary structural interface for load transfer and ecological performance, primarily through its textured inner and outer surfaces.

Once printing is complete, SCC is poured into the annular cavity between the central core and the outer shell. This hybrid strategy allows the printed geometry to focus on form and ecological function, while the cast concrete ensures mechanical robustness.

This integrated geometrical logic and fabrication sequence reflects the project's hybrid philosophy: using digital fabrication to control both external and internal behavior, achieving a high-performance, bio-functional, and constructible coastal infrastructure solution.

Table 1: Dimensional specifications of the eco-dike prototype components

Component	Height (cm)	Diameter (cm)
Outer shell (Top and bottom sections)	15cm_ each	140
Outer shell (twisted middle section)	30	100
Sinusoidal internal geometry	60	60 (5cm Thickness)
Central Star core	60	43
Hole size	60	35

The prototype will be printed using a layer height of 1.5 cm and a bead width of 4 cm, based on the nozzle configuration used in lab-scale testing.

3.2 Surface and ecological features

The unit's exterior includes biomimetic textures and sculpted cavities, inspired by marine organisms and ecological infrastructure such as the Living Seawalls. These features are specifically designed to trap moisture, collect wind-blown sand, and support the rooting of dune vegetation. Selected cavities serve as planter zones, enhancing early vegetation establishment and long-term stabilization through plant-sediment interaction. The self-compacting concrete will contain coarse aggregates to improve surface roughness, particularly within the annular cavity between the printed shell and the sinusoidal wall. While most of the sinusoidal insert and the shell remain separated by the SCC core, partial contact will occur in specific zones, such as the middle section, ensuring mechanical interlock and improved cohesion. Once cured, this textured concrete surface will promote sand retention and root anchorage, particularly for dune grasses such as Ammophila arenaria, thereby enhancing the ecological performance of the prototype from within.

3.3 Modular Interlocking Logic

The unit’s edges are shaped to **interlock mechanically** with neighboring blocks, allowing quick and stable assembly on-site without the need for complex anchoring systems. Hill block systems inspired this modular logic, allowing the prototype to adapt flexibly to different site geometries. It also simplifies repair and replacement, ensuring long-term maintainability.

3.4 Material Integration

The prototype will be fabricated using a layered 3D printing process with a mortar-based bioreceptive mix to define the outer shell, followed by in-situ casting of an environmentally friendly SCC into the cavity for structural integrity. This hybrid approach enables the shell to carry ecological and geometrical complexity, while the SCC core ensures mechanical performance. The 3D-printed shell will be developed with bioreceptive properties in mind, in alignment with the Material formulations studies in D15.1 to support external ecological interaction. The SCC will be optimized for mechanical strength and internal ecological function, using coarse or recycled aggregates to promote ecological functionality where applicable.

Lifting hangers were integrated into the prototype during the SCC casting phase to facilitate safe transport and on-site handling. These hangers were fixed within the cavity before the concrete was poured, ensuring they were securely embedded into the structural core. Their placement was coordinated with the unit’s center of gravity for balanced lifting and precise positioning during installation. This solution ensures the modular units can be moved efficiently and safely without damaging the printed shell or compromising structural performance.

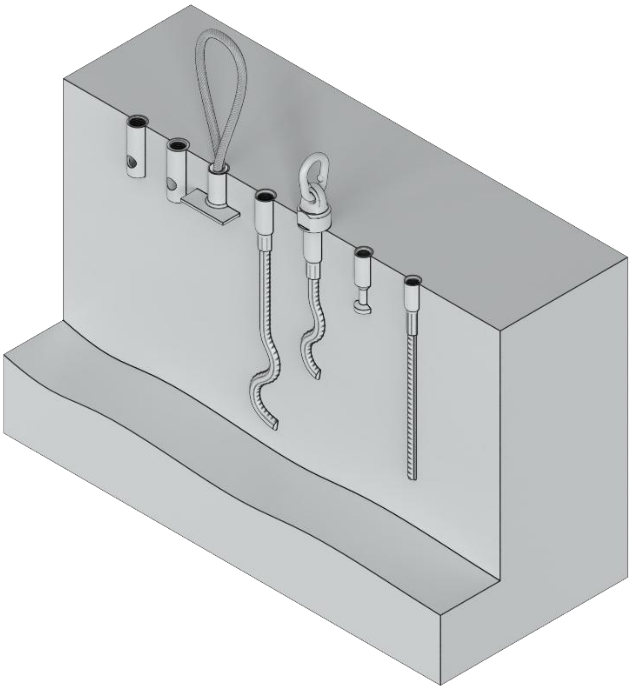

Figure 7: Lifting anchor embedded in a precast concrete element

3.5 Fabrication Setup and Scaling Considerations

The full-scale eco-dike prototype will be fabricated using a robotic concrete printing process based on a setup developed at Ghent University. The fabrication will employ an ABB IRB 6600 robotic arm, programmed in RAPID using the RobotWare environment. Printing paths are generated through Grasshopper (Rhino), where the sliced 3D geometry is converted into XYZ coordinates and tool orientations for layer-by-layer extrusion.

The printing strategy follows an inside-to-outside sequence, beginning with the central star-shaped cavity and progressing outward to the rotational sinusoidal geometry and the octagonal outer shell. This sequence ensures continuous nozzle movement, reduces the risk of collisions, and maintains extrusion stability throughout the print.

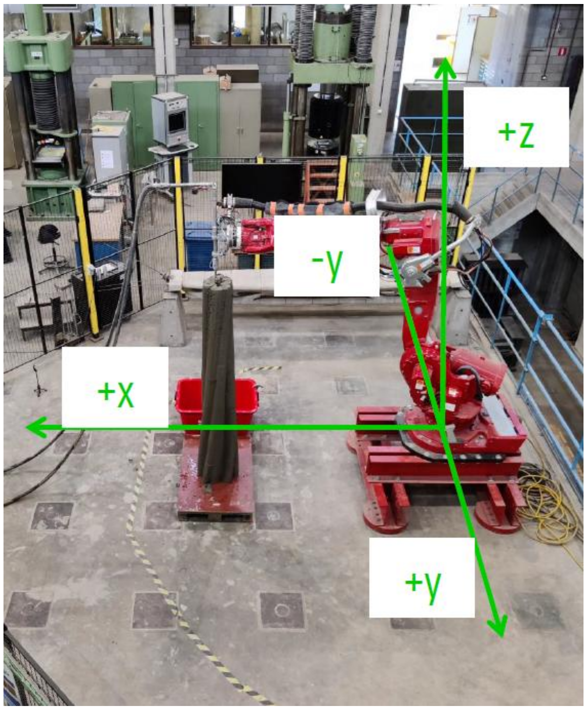

Figure 8: ABB IRB 6600 Robot

A custom extruder will be mounted on the robotic arm, defined through standard tool data parameters, and operated relative to a fixed work object (wobj) coordinate system. The robot will execute MoveL (linear movement) commands to follow precise toolpaths, using quaternion-based orientation control to maintain smooth transitions and prevent kinematic singularities.

While preliminary tests are conducted at laboratory scale, including slicing logic, geometric definitions, and toolpath code , the final design will first be printed and tested in-Lab. After this validation phase, the setup will be transferred to an external industrial fabrication partner for large-scale production. This ensures the prototype can be fabricated using existing large-format robotic systems, aligning with the DuneFront project's goal of delivering scalable, field-deployable nature-based infrastructure.

4. Site and Implementation Process

The eco-dike prototype is planned for installation at a pilot site in **De Panne**, Belgium, where it will be tested under realistic coastal conditions. De Panne is characterized by a **30° dune slope**, dynamic sand movement, and periodic exposure to wave forces—an ideal environment to evaluate the performance of hybrid blue-grey coastal infrastructure.

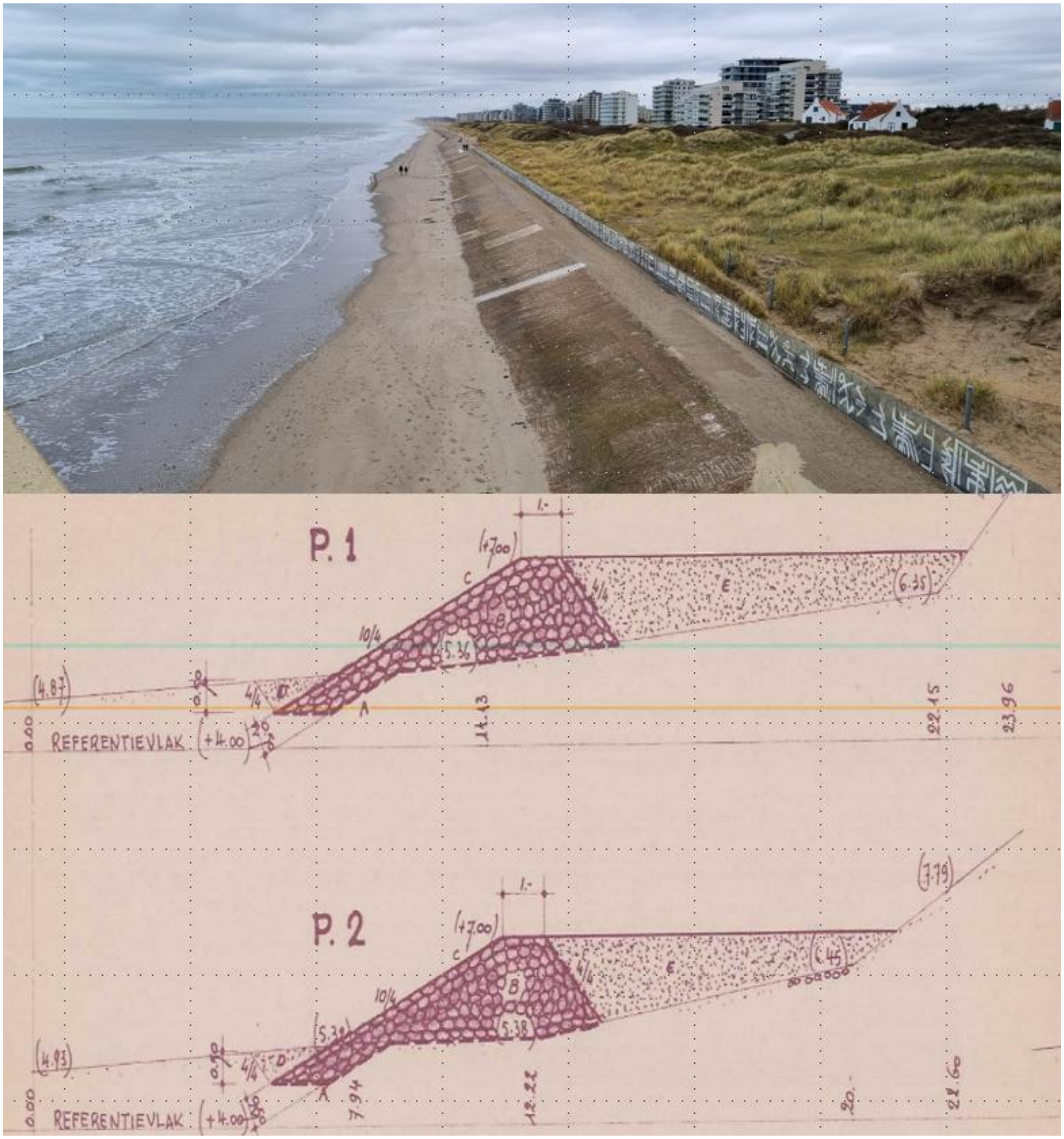

Figure 9: De Panne site

Figure 10: Proposed layout of the modular eco-dike units on a sloped surface, simulating their placement at the De Panne pilot site.

In this visualization, the elements are shown slightly spaced for clarity. In reality, the units will be installed more tightly connected to ensure structural continuity and hydraulic performance along the dike slope.

The De Panne implementation will serve as a comparative demonstration of three protective systems:

- The DuneFront hybrid prototype (eco-dike unit with bioreceptive design),
- A conventional rock-based revetment.
- An existing commercial solution used in local coastal defense.

This side-by-side comparison will enable assessment of ecological impact, sediment interaction, stability, and long-term resilience across different technologies.

The installation will begin with light ground preparation, including clearing and stabilizing a segment of the dune-dike interface. Units will be transported using pre-installed lifting anchors, aligned manually or with light machinery, and deployed in series to form a partial eco-dike segment. The interlocking geometry eliminates the need for deep foundations or heavy anchoring systems. Three test areas will be prepared, each corresponding to one of the comparative pilot strategies. Sensors and visual monitoring systems will be installed to assess performance over time.

5. Conclusion

This deliverable documents the current stage of development for a novel hybrid eco-dike prototype in WP15 of the DuneFront project. The design integrates bioreceptive cementitious materials, a modular interlocking system, and digitally fabricated geometry to support both hydraulic protection and ecological enhancement in coastal environments.

At this stage, the prototype has been mostly modelled and dimensioned and will be fabricated at lab scale using robotic 3D printing and a hybrid SCC infill strategy. Initial printing tests will be conducted to validate the geometric logic and layer-by-layer manufacturing sequence. Ongoing work is focused on optimizing robotic toolpaths, fine-tuning extrusion parameters, and ensuring material consistency for reliable fabrication and structural performance. The digital workflow, including code generation and slicing for robotic control, is also being refined to ensure scalability and repeatability.

The prototype's implementation at the De Panne test site is planned for the next phase. Before this deployment, further lab testing will continue to evaluate the interface between the printed shell and SCC core, surface roughness for ecological colonization, and lifting and handling methods. Results from this optimization phase will inform the final product version to be transferred to an industrial fabrication partner.

The progress documented in this report forms a critical link between material innovation and field deployment, paving the way for a nature-based, digitally manufactured solution to coastal resilience.

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