A New Framework for Artificial Coral Reef Design

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Abstract: The tropical coral reef ecosystem is currently facing an unprecedented ecological crisis (HUGHES et al. 2017 & HARRIS et al. 2006), and it remains unclear how reef regeneration projects are progressing without efficient artificial reef designs that hold the long-term potential to become a fully integrated part of the coral reef ecosystem. As a response to the urgency and relevance in preserving coral reefs, the paper introduces a novel framework for artificial coral reef design as a differentiated approach towards artificial coral reefs − demonstrating the feasibility of digitally designing such 'living architecture' according to multiple context and performance parameters. The framework combines many technical components such as algorithmic design, high precision underwater monitoring, performance analysis and simulation, that were tested and combined in such a way for the first time. The main contributions to the field include the Ecosystem-aware design approach, Key Performance Indicators (KPIs) for coral reef design, algorithmic design and fabrication of Biorock cathodes, new high precision UW monitoring strategies, long-term real-world constructed experiments, new digital analysis methods and two new front-end web-based tools for reef design and monitoring reefs. Additionally, the framework offers a theoretical and practical background for computational design, ecology-led design and marine conservation.

Keywords: Artificial coral reefs, computational modelling, high precision underwater monitoring, ecology in design.

1 Introduction

Tropical coral reefs, one of the world's oldest ecosystems which support some of the highest levels of biodiversity on the planet, are currently facing an unprecedented ecological crisis during this massive human-activity-induced period of extinction (KNOWLTON 2001, SAHNEY & BENTON 2008). Hence, tropical reefs symbolically stand for the destructive effects of human activities on nature (HUGHES et al. 2017 & HARRIS et al. 2006). Artificial reefs are excellent examples of how architectural design can be combined with ecosystem regeneration (RINKEVICH 2005 & BOSTRÖM-EINARSSON et al. 2020). As three-dimensional subsea structures, they substitute the morphology of destroyed reefs (due to land development, storms, bleaching, etc.), and increase the size of the existing coral reef cover. Their main potential lies in biogenic construction methods and their biodiversity promoting structural three-dimensionality (CARR 1997). In architectural practice, there are outstanding artificial coral reef projects that integrate architectural design and ecosystem restoration to promote growth and biodiversity in coral reefs, e. g., a 3D printed modular reef to mimic natural habitats by ALEX GOAD, Reef Design Lab (Mars). However, most of the existing approaches are inadequate in terms of their structural three-dimensionality and the inclusion of biogenic construction methods. They fail to promote marine habitats and biodiversity in the long-term (SHEPPARD 2018). Such artificial reefs rather increase threat levels and cause permanent harm to the marine environment. In contrast, the new framework for artificial coral reef design represents an entirely new approach to artificial coral reef design by including the requirements of the coral reef ecosystem in the design process, and by precisely studying the relationships between architectural and ecological aspects (e. g., how a surface design and material compo-

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sition can foster coral larvae settlement, or how structural three-dimensionality enhances biodiversity). Further, it integrates an underwater (UW) monitoring process to gain feedback about adaptation and knowledge about the ecosystem and make it available for design. Additionally, the framework provides missing key attributes for more sustainable artificial coral reefs by introducing a set of indicators of success for artificial coral reef design.

One of the greatest challenges can be found at the interface between the artificial and the complex and temporal nature of natural systems, especially with respect to the B-rep modelling legacy of computational modelling. Thus, the framework has integrated strategies on how to apply digital practice to realise what is an essential bulwark in an unequal battle to retain reefs in impossibly challenging times. Beyond the main question of integrating computational modelling and high precision monitoring strategies in artificial coral reef design, the framework links multiple techniques and methods to support future research and practice in ecology-led design contexts. The following empirical experimental methods were applied:

(1) **Algorithmic coral reef design:** This research area deployed computational design and fabrication strategies for component-based artificial Biorock reefs. Biorock reefs use electrodeposition of minerals in seawater to accumulate $CaCO_3$ around metallic structures (HILBERTZ 1979)[1]. As such, growth algorithms from nature are applied within a 3D CAD system to explore geometrical configurations for nature-like and optimised Biorock cathode designs.

(2) **High precision underwater (UW) monitoring:** This area focused on the exploration and development of a high precision UW monitoring workflow for artificial reef prototypes. Most recent high precision survey techniques such as UW laser scanning, UW photogrammetry and CT scanning were tested to create high precision digital twin models for digital survey and analysis purposes.

(3) **Computational modelling and simulation:** The research area focused on how computational modelling and simulation methods from the architectural practice can be applied in a totally new context − for the development of a computational framework for artificial reef design. This includes the investigation of corresponding computational design and performance analysis strategies, the definition of Key Performance Indicators (KPIs), an appropriate software framework for development, data conversion of massive 3D data sets, less process-intensive solutions, as well as the display of simulation results through front-end tools that allow the users to interface through the framework with the developed system.

(4) **Artificial Reef Prototypes (ARPs) in Gili Trawangan, Indonesia (2012-today):** Long-term experiments in a real-world tropical coral reef ecosystem in Indonesia are the object of inquiry for UW survey and digital performance analysis processes which result in defining KPIs for ARP optimisation (Section 2.3). They also validate the overall approach of the framework.

Based on the main methods, multiple discrete sub-methods and techniques were developed in seventeen computational experiments and applied in a way in which many are cross valid and integrated into the overall framework as a significant contribution to the field (Section 2.2 & 2.3). Other main contributions include the Ecosystem-aware design approach, KPIs for

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[1] Electrolysis not only generates the construction material but also binds harmful CO_2 in seawater (HILBERTZ 1992).

coral reef design, algorithmic design and the fabrication of Biorock cathodes, new high precision UW monitoring strategies, long-term real-world constructed experiments, new digital analysis methods and two new front-end web-based tools for reef design and monitoring reefs (Section 3).

In summary, the paper presents key aspects of the new framework that was developed in the author's dissertation: *'A Framework for Artificial Coral Reef Design: Integrating Computational Modelling and High Precision Monitoring Strategies for Artificial Coral Reefs − an Ecosystem−aware Design Approach in Times of Climate Change'* (VOGLER 2020). It is a response to the urgency of marine species preservation in a massive extinction period. In comparison with existing approaches, the new framework offers a differentiated approach towards artificial coral reefs by demonstrating the feasibility of digitally designing such living structures. It takes into account multiple criteria from ecology and architecture addressing the requirements of human and non-human stakeholders. It also provides an in-depth critical discussion of computational design and architecture in the context of ecosystem regeneration and Planetary Thinking (Section 4). In that respect, the framework functions as a both theoretical and practical background for computational design, ecology and marine conservation − not only to foster the design of artificial coral reefs technically but also to provide essential criteria and techniques for conceiving them.

2 Methods

The framework was developed by an experimental exploration process in an interdisciplinary collaborative setting, connecting experts from architecture, marine biology, material science, geomatics for underwater applications and local Indonesian fisherman and professional divers. It is composed of a practical and a theoretical part. The practical part includes seventeen computational modelling and simulation experiments as well as real-world physical UW implementations (Artificial Reef Prototypes – ARPs). The theoretical part contextualised and integrated all design and monitoring experiments to encounter domain-specific theories. The following section introduces the main methods and techniques for the development of the new framework (Section 2.2 & 2.3) which are described in more detail in the author's dissertation. It starts with an introduction to the field study site (Section 2.1).

2.1 Field Study Site in Gili Trawangan

The site of the key case study for the design and construction experiments is located in the Bali Sea, fifty metres off the shoreline of the small island of Gili Trawangan, Indonesia (Figure 1). The site exemplifies an area where tropical coral reefs are typically important sources of income for the local fishing and tourism industry, but, at the same time, are seriously threatened due to global warming over the past fifteen years. Thus, coral restoration and conservation is a priority in this region (WILLIAMS 2019). The site offers ideal conditions for installing long-term design experiments and for UW monitoring activities because a local NGO established in 2000 an adequate infrastructure for reef conservation efforts based on Biorock technology. As the world's second-largest Biorock reef restoration site, Gili Trawangan offers a fully operating underwater infrastructure for Biorock reefs such as underwater cables and costly anodes made out of titanium, and floating solar panels as power supply. Furthermore, local authorities, the local community and local businesses are in favour of reef conservation work at the Gili Islands. As such, they provide permission and funding for material, maintenance, and dissemination activities. Finally, the key to a successful UW monitoring process based on imagery data is visibility (VOGLER 2019). At the chosen UW site, visibility of up to thirty-five metres has been measured offering exceptional conditions for UW monitoring. In summary, the proposed UW site is ideal not only to implement prototypes but also to advance the framework, including integratively testing and validating all components, taking into account local environmental challenges (annual storm and coral bleaching events, earthquakes and tremors, and biodiversity decline through predators).

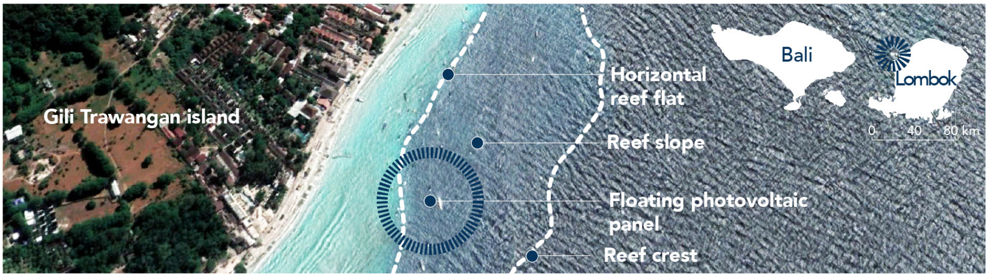

Fig. 1: The location of the field study site (blue circles) off the shoreline of the Gili Trawangan island in the Bali Sea, Indonesia (8°21'32.7"S 116°02'32.4"E)

2.2 The New Framework for Artificial Coral Reef Design

Research shows that ecosystem regeneration approaches for artificial coral reef regeneration are already highly topical amongst many disciplines and have just started to gain relevance in architectural and engineering practice during the past ten years. However, there are significant gaps regarding consideration of the requirements of coral reef ecosystems and the implementation of monitoring strategies for artificial reefs which were addressed by the new Artificial Reef Design Framework (ARDF). ARDF has many technical components that were tested and combined in this way for the very first time (Figure 2): (1) Algorithmic design and fabrication, (2) UW monitoring, (3) performance analysis and evaluation, (4) Ecosystem-aware design system, and ultimately (5) validation. The main goals of the framework are to establish a meaningful connection between design and high precision monitoring actions, and the development of a Computational modelling and Simulation environment, which makes knowledge about tropical coral reefs available for design aiming at facilitating a new level of interaction between architecture and the coral reef ecosystem.

The key challenge was to integrate all five components into a unified workflow. This process came along with several sub-challenges: First, custom algorithms for a coherent computational design and fabrication workflow needed to be developed. Second, long-term and high precision UW survey methods had to be tested and deployed, and strategies for digital performance analysis of high precision 3D models from UW scan data were explored. Further, KPIs needed to be defined and validated. Third, to facilitate the framework's Simulation Environment, the design problem had to be reformulated based on the experimental findings of the ARP design experiments. Finally, to validate the framework, an interface was developed within a standard CAD modelling environment to allow not only architects but also marine conservationists and other stakeholders to interact with the new system. To tackle these challenges a series of design, monitoring, performance analysis and simulation experiments were necessary. They are introduced in the following section 2.3.

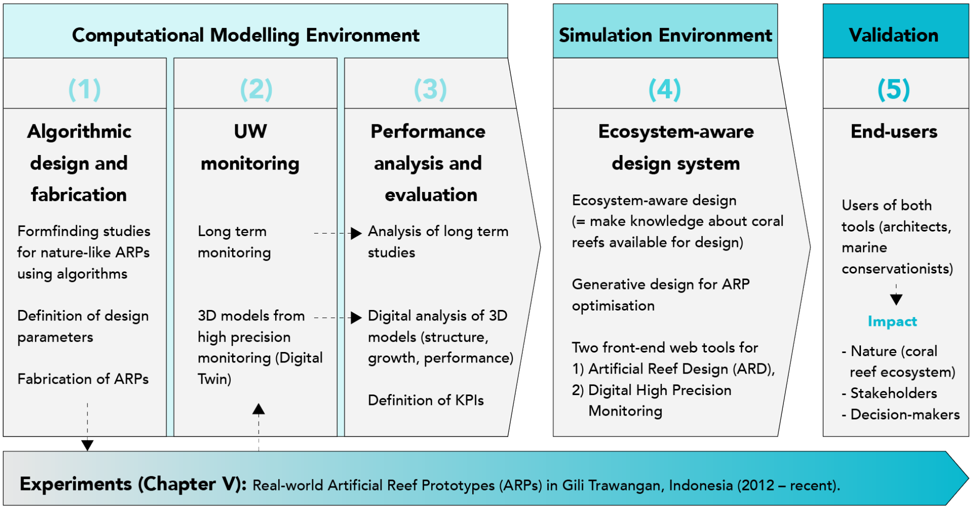

Fig. 2: The Artificial Reef Design Framework (ARDF) and its five main components

2.3 Seventeen Computational Experiments

Computational experiments were relevant for empirically developing ARDF and its components, as well as the corresponding theoretical background. Furthermore, the knowledge gained from the conducted experiments defined the main indicators of success for artificial reef design – the KPIs. KPIs are not only crucial for evaluating existing artificial reef structures but also for the development of the framework's Simulation Environment (Figure 3).

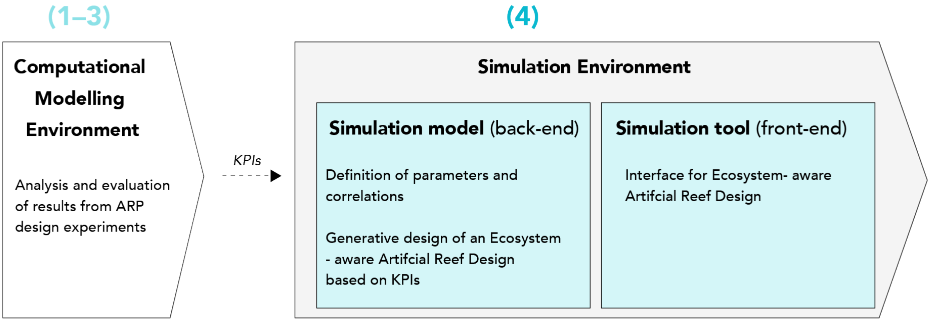

Fig. 3: The framework's Simulation Environment

The following sub-sections introduce the experimental methods that were used for the development of each component of the framework.

Algorithmic design and fabrication: The form and structure of traditional Biorock cathodes made from rebars stand in contrast to intricate configurations of naturally grown coral reef formations (Figure 4). The most similar pattern found in Scleractinian corals is Lindenmayer system fractals (L-systems). L-systems allow the modelling of fractal-like forms in realistic plant models and natural-looking organic forms and have not been applied yet in artificial coral reef design. By varying a small number of parameters including branching angle, the distance between nodes or branch points, tree growth patterns can be generated (ROZENBERG & SALOMAA 1980). In contrast to bulky traditional Biorock cathodes, the method proposes component-based cathode designs developed through an L-system algorithm written in GHPython within Rhino's 3D modelling environment which is then converted into fabrication data.

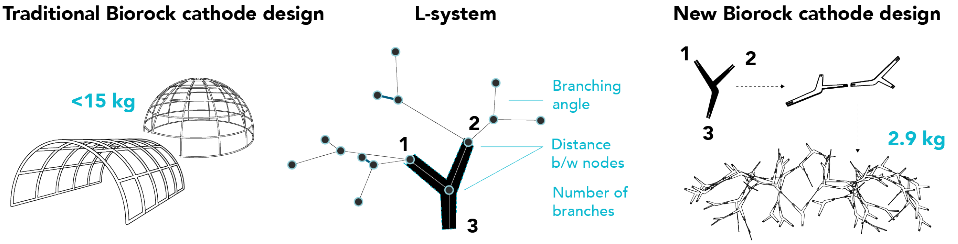

Fig. 4: A new approach to Biorock cathode design

The structure can be assembled from multiple lightweight steel elements and extended infinitely (Figure 5). The initial size of the ARP was 80 cm × 100 cm × 60 cm. In 2017 it was extended 2017 to a size of 160 cm × 200 cm × 60 cm.

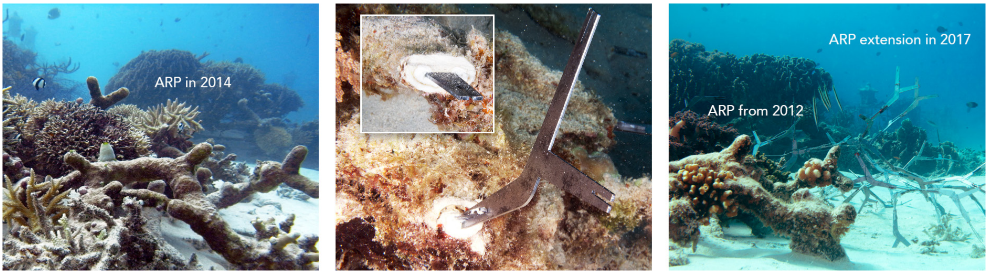

Fig. 5: Artificial Reef Prototype (ARP) in 2014 (left) and its extension (right) in 2017 in Gili Trawangan, Indonesia. The removed $CaCO_3$ layer of the five-year-old structure exposed a fully functional push-to-fit connection to connect new construction elements with an existing structure.

High precision UW monitoring: In the engineering practice, excellent UW survey technologies and tools have been developed for capturing intricate details of corals and coral reefs, e. g., the autonomous UW ROV called 'SeaVision' based on subsea LiDAR (Kraken Robotics), or the autonomous USV 'Reef Rover' based on UW photogrammetry (Reef Rover). However, an application of any kind of these high precision techniques for monitoring artificial coral reefs is still missing. This can be attributed to this being a relatively new field (artificial reef design), but also due to a lack of time and financial resources (e. g. costly equipment, difficult to reach UW sites), and a missing long-term interest (e. g. from governments that were just interested in short-term greenwashing). Curt Storlazzi, Geologist at the Pacific Coastal and Marine Science Center (Santa Cruz, United States), says in regards to coral reefs surveys, that there is an indispensable need to more precisely monitor coral reefs to model, protect and preserve them (STORLAZZI et al. 2019). The presented method provides an entirely new workflow for high precision monitoring for (artificial) coral reefs. It includes research into the latest UW surveying technology (UW LiDAR laser scanning, UW photo- and videogrammetry at close range and CT scanning) and on-site experiments to test its applicability to (artificial) coral reef surveying (VOGLER et al. 2019 & VOGLER 2019). The results are high precision digital twin 3D models (point cloud and voxel models) that provide detailed information about the surface- and material configurations, size and structure, as well as the biodiversity index of the artificial structure (Figure 6).

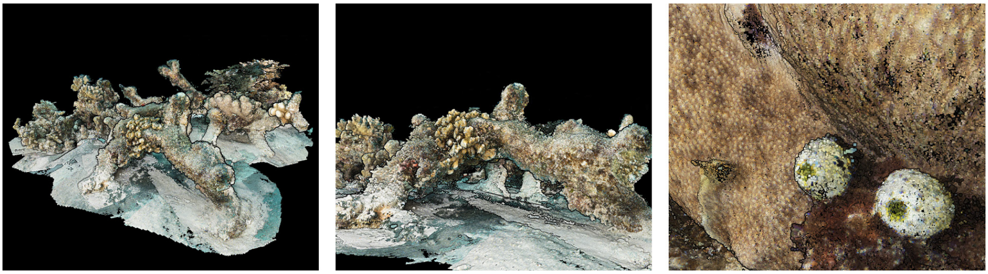

Fig. 6: Digital high precision twin model in a standard web browser (WebGL)

Furthermore, the method also implemented a web tool for massive 3D point cloud display based on the Potree Converter technology in a standard web browser. As an open and accessible interface, it allows precise digital surveys of the collected UW monitoring data and thus, feedback for design[2] (Figure 7). Furthermore, the monitoring method includes long-term UW monitoring strategies that identify site-specific key stressors from matching ARP image data with open databases from climate charts.

Performance analysis and evaluation: In marine conservation, particularly in artificial reef design, an approach to performance analysis of digital 3D data is still missing. This can be due to a lack of resources (knowledge and financial resources) and the still-missing systematisation of design, monitoring and analysis. To address this problem, performance analysis strategies based on the latest digital methods were developed for reef design. The analysis results aim to increase knowledge about the relationships between the shape and the structure of the artificial coral reef (architecture) and its performance in the UW environment (ecology). Of particular interest is, which design decisions foster biodiversity, growth, larvae settlement and the distribution of nutrients (turbulences).

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[2] ARPs can be surveyed at an original resolution on the project's webpage: https://3d.artificialreefdesign.com/potree/reef/.

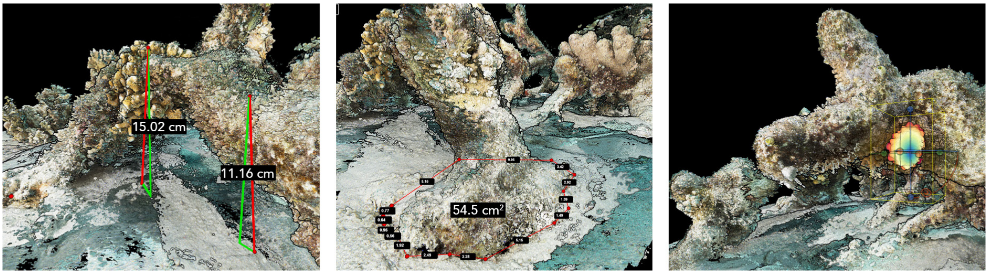

Fig. 7: Web tool for digital high precision survey (e. g. distance measurements, area, and volume)

Such information is crucial to better understand the spatial-temporal dynamics for designing such living structures. However, the analysis of high precision 3D data from UW scans comes along with major technical challenges such as the visualisation of massive 3D point cloud/ voxel datasets, file conversion (e. g. point cloud or voxel data to polygonal mesh data), and the processing of large 3D data, which needed to be addressed. Sub-methods from the architectural and engineering practice such as Finite Element Analysis (FEA), Isogeometric Analysis (IGA), and hydrodynamic modelling were applied in a totally new context – to the analysis of digital twin models of artificial reefs. Furthermore, alternative 2D and 3D analysis methods for the determination of (surface) roughness values, an indicator for higher levels of biodiversity were explored. KPI determination is another outcome of the performance analysis experiments.

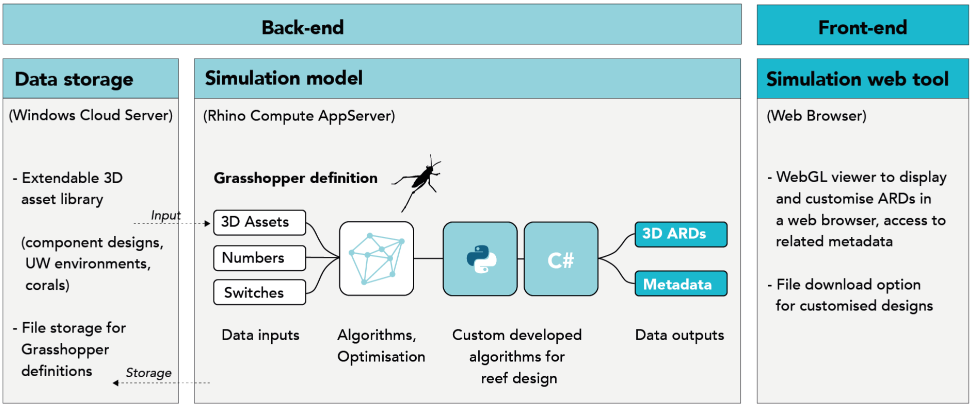

Fig. 8: The system architecture of the framework's Simulation Environment

The Simulation Environment – an Ecosystem-aware design approach: The framework interfaces with the stakeholders through a software-independent front-end web tool, developed in RhinoCommon, an open software framework for CAD tool development (Figure 8). It can be accessed through a standard web browser. As a software- and hardware-independent solution, it allows interdisciplinary users to be equally involved in the design decision-making process. KPIs are an intrinsic part of the developed Grasshopper algorithms that simulate new Artificial Reef Designs (ARD). The algorithms are computed on a back-end service through the Rhino.Compute AppServer, a node.js server acting as a bridge between client apps and private Compute.Rhino3D servers.

Besides design simulations of new artificial Biorock reefs, the front-end tool outputs numerical metadata relevant to the architectural design and also for ecology (e. g. three-dimensionality, amount of material, etc.).

3 Results and Discussion

The main contributions of the framework include the Ecosystem-aware design approach, KPIs for coral reef design, algorithmic design and fabrication of Biorock cathodes, new high precision UW monitoring strategies, long-term real-world constructed experiments, new digital analysis methods and two new front-end web-based tools for reef design and monitoring reefs. They are described in more detail in the following sections.

3.1 ARDF as an Ecosystem-aware Design Approach

The framework's core contribution is the development of an integrated computational modelling, high precision UW monitoring and analysis approach. In contrast to other contemporary digital artificial reef design approaches, the ARDF has equally considered the integration of all five components − algorithmic design and fabrication, UW monitoring, performance analysis and evaluation, Ecosystem−aware design system, and validation − from the very beginning. By unifying computational design, UW monitoring and simulation processes into a single system, it allows the development of well-adapted, cost-efficient and sustainable component-based cathodes. These successfully perform structurally and ecologically long-term as artificial coral reefs in a tropical underwater environment, without creating artificial coral reef structures that contaminate or even harm the coral reef ecosystem. Therefore, human and non-human stakeholders benefit from the ARDF outcome equally.

3.2 Key Performance Indicators of Artificial Reef Design

In total, six KPIs as indicators of long-term success are defined and are one of the principal achievements of the framework. They are not only a new evaluation system for existing artificial coral reefs but aimed to foster a more responsible design of future artificial reefs (Table 1).

3.3 Algorithmic Design and Fabrication Strategies for Biorock Cathodes

Another result is an alternative approach to conventional Biorock cathode design using algorithms from nature (such as L-systems) and digital fabrication strategies. They fostered the development of artificial reef structures that do not merely mimic the form of a natural reef but are the result of an observation process of natural forms, structures and functional characteristics found in coral reefs. The resulting ARPs are component-based Biorock cathodes made out of smaller, lightweight construction elements from steel whose structural system heavily differs from conventional Biorck reefs with respect to its shape, assembly, and three-dimensional structure − a benchmark that ensures the improvement of ecological and structural performance in the marine environment. Furthermore, the new cathode designs provide multi-scalar spaces, a characteristic found in natural reefs of high biodiversity, and its mate-

Table 1: KPIs as major indicators of success for a more sustainable reef design

KPIs	KPI description
KPI 1 Adaptation	KPI 1 evaluates the capacity of the new ARP to adapt to conditions of the given UW site including the existing coral reef ecosystem, and to the requirements of e. g. Biorock Technology.
KPI 2 Performance	KPI 2 evaluates the structural design of the ARP and its ability to withstand UW tides, currents, waves and extreme weather events. It includes symmetry and structural equilibrium, size, and material of the designed ARP.
KPI 3 Biodiversity	KPI 3 assesses all parameters that foster the emergence of biodiversity in new ARPs designs such as three-dimensionality, spatial diversity (the creation of multiscalar spaces where marine organisms can hide and reproduce), and surface roughness values with an impact on the settlement of coral larvae.
KPI 4 Growth	KPI 4 evaluates the design's ability to promote the growth of coral and the $CaCO_3$ layer (created by the Biorock technology). This includes the assessment of the quality of the provided places where corals can grow and the size of the gross surface area available for the $CaCO_3$ layer to grow.
KPI 5 Sustainability	KPI 5 assesses the material and CO_2 savings of the design, fabrication, transportation, and installation process.
KPI 6 Efficiency	KPI 6 evaluates all of the cost and time saving associated with successful implementation, including manufacturing, materials and transportation.

rial saving is up to 80 %. Once overgrown with a $CaCO_3$ and a marine layer, it almost appears as a natural reef structure.

Additionally, its long-term success as part of the coral reef ecosystem at the shoreline of Gili Trawangan (2012 – today) approved the new design approach for Biorock cathodes in this research (VOGLER 2018) (Figure 9).

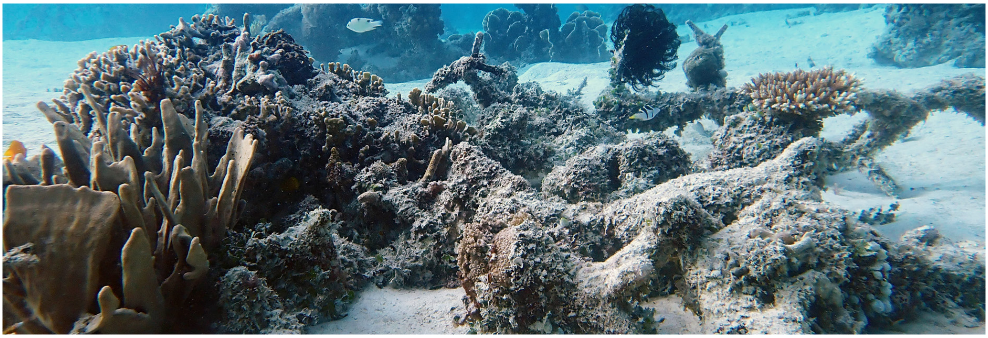

Fig. 9: ARP in August 2021. Its appearance resembles a natural reef.

3.4 New High Precision UW Monitoring Strategies for (Artificial) Coral Reefs

With the development of an entirely new workflow for high precision UW monitoring for (artificial) reefs including the latest cutting-edge technologies such as UW LiDAR laser scanning, UW photo- and videogrammetry at close range, and CT scanning, the framework contributes to the field of marine science and engineering. The resulting 3D models are massive point cloud and voxel models of millimetre and submillimetre precision, and therefore, are one of the most precise and detailed existing (artificial) coral reef 3D representations. The new workflow includes low-cost solutions for UW data collection, data processing, and the conversion of massive 3D data for display. In a larger context, the framework makes a crucial contribution to the field of ecology-led design by illustrating the importance of the incorporation of appropriate monitoring strategies for (artificial) reefs.

3.5 Long-term Real-world UW Experiments

Real-world UW experimental prototypes (ARPs) are responsible for the successful implementation of all computational experiments. They not only provide the basis for the empirical studies but also validate the developed system. Additionally, long term real-world experiments demonstrate the significance of prototypes and their evaluation before large-scale interventions are carried out in a highly endangered ecosystem.

3.6 New Digital Analysis Methods for (Artificial) Coral Reefs

With the identification of analysis methods from architectural practice which can be applied to reefs, the framework contributes to establishing an entirely new digital analysis workflow for artificial reefs.

The applied methods foster a better understanding of whether a structural design is stable and withstands the acting loads in the UW environment or not, and quantifies the artificial reef's performance in respect to its three-dimensionality, surface roughness, and hydrodynamics (how the reef's morphology affects the movement of particles). Specifically, hydrodynamic analysis revealed a relationship between the reef's morphology (on different scales) and its ability to dissipate a significant amount of kinetic energy (e. g. from currents, waves, tides, waves, or swells) as well as promote biodiversity (distribution of coral larvae and nutrients) and therefore identified that a nature-like morphology plays a key role in artificial reef design (Figure 10).

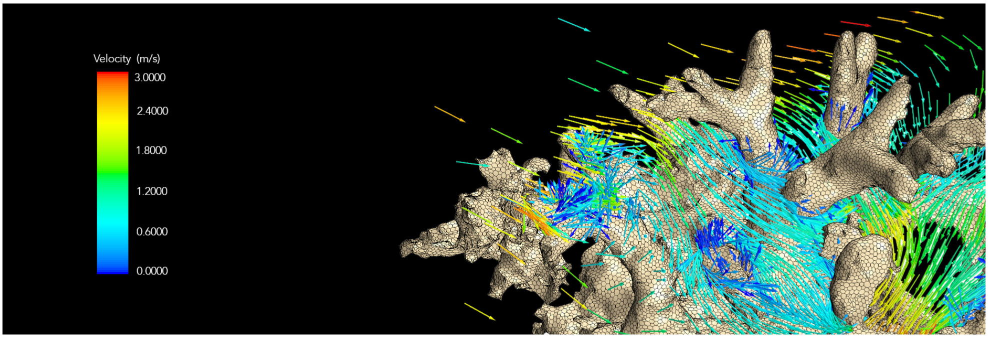

Fig. 10: The hydrodynamic particle simulation model with Siemens STAR-CCM+ software shows how geometrical configurations have influenced particles to slow down (from red- 30000 m/s to blue- approximately 0.2 m/s)

3.7 Two New Front-end Web-based Tools for Reef Design and Monitoring Reefs

As a last result, the new framework contributes not only to a holistic design approach for artificial coral reefs but also to a holistic approach to interdisciplinary collaborations. In fact, the research has established new relations and networks for artificial coral reef design. In this context, the development of common software interfaces for a cross-disciplinary team involved in artificial reef design changed the existing paradigm. Instead of separating each discipline for specific tasks, these interfaces promote and strengthen the dialogue and knowledge transfer between them. Both developed interfaces – a) for the digital survey of UW high precision data, and b) for designing artificial reefs based on the principles of the developed framework – are web tools that can be opened using a hyperlink in a standard web browser. This means that they are software- and hardware-independent solutions that no longer restrict who can participate in the design decision-making process. Furthermore, the tools developed also enable team members without prior knowledge or access to special 3D modelling software to equally contribute to the artificial reef design outcome.

4 Conclusions and Outlook

The key research goals of the new ARDF have been validated through long-term real-world full-scale demonstrators (ARPs) in Gili Trawangan (2012-today). Accordingly, the main goals- the exploration and integration of computational design, high precision UW monitoring, and simulation strategies for component-based artificial (Biorock) reef system with the challenge to equally address the requirements of the coral reef ecosystem (regrow corals in the Bali Sea), the architectural design, and the stakeholders, have been successfully demonstrated. Up to this point, there is no equivalent to the demonstrated fully integrated computational design, UW high precision monitoring and simulation process for artificial (Biorock) reef design, which has yet been to be demonstrated to operate over the long term as part of the natural coral reef ecosystem at 1:1 scale. In summary, there are seven main contributions that the ARDF has made starting from the Ecosystem-aware design approach to two new front-end web tools for reef design and monitoring (Section 3).

In future research, the proposed ARDF could be improved regarding its applicability for large-scale reef formations. In this realm, the possibility for a) an effective in-situ manufacturing system of such (robotics for the production, consideration of alternative fabrication methods such as $CaCO_3$-based additive manufacturing) for a larger number of construction elements; b) the establishment of long term collaborative reef maintenance programs together with the local community; c) and a fast and efficient automated pipeline for UW monitoring (robotics for operation) would need to be investigated. Furthermore, a GIS reference system for (artificial) coral reefs needs to be developed to enable the operation of remote vehicles for construction, maintenance and survey tasks. Lastly, for a true multi-criteria optimisation process, trade-offs between KPIs need to be further defined and classified (e. g. what happens if a design`s structural and ecological performance is high, but fabrication is too costly etc.). Such a process could then lead to a true data-driven design-decision support system for artificial coral reefs.

In summary, the research contributed to critically assess the existing anthropocentric role model in architecture (Vitruvius to Neufert) in times of climate change concluding that the self-perception of the profession has to change − for instance, in a way that boundaries between disciplines are repealed through interdisciplinary collaborations and interfaces. It could also change by introducing new relations between technology, ecosystems, and humans, that those outdated role models are replaced by holistic approaches that eliminate the dichotomy between humans and nature. Finally, this could be done in a way that establishes better legal frameworks and business models for ecosystem regeneration projects.

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