Supporting Information:

1.0 Considerations when using 3D printing technology

1.1 3D scanning and Printing

Different 3D scanners are designed for different purposes, with trade-offs between the size of the objects that can be scanned and the resolution of the scan. For example, some scanners are designed to scan objects as large as cars and may not capture fine-scale details of a biogenic habitat sample. Scanning biogenic objects requires the focal sample to be the appropriate size for a given 3D scanner (i.e. within the spatial limitations of a scanner) that provides the necessary resolution of morphological features. As mentioned in the MS, these seeming limitations can be remedied by modularizing the 3D scanning and printing process to scan individual components to later assemble during the file manipulation phase or once printed. Based on trials using various 3D scanners, we recommend scanning systems that capture micro-habitat detail when creating AH to test habitat selection cues. The *2020i Next Engine Desktop 3D Scanner* required little manipulation after scanning and upheld ecological integrity of the design shape. A variety of 3D printers were used to test printing capabilities and features. The first printers tested were the *Form II resin printer* (**Fig. S1A**) and the *Stratasys J750 printer* (**Fig. S1B**). The main advantages of these printers are their ability to print objects with extremely high resolution. However, these printers and printing materials are often more expensive, and an impractical solution to reducing cost and increasing scalability. Extrusion-based printers and printing material are more accessible and affordable. They also have the option of easily changing printing material filament, making them adaptable (**Fig. S1C**).

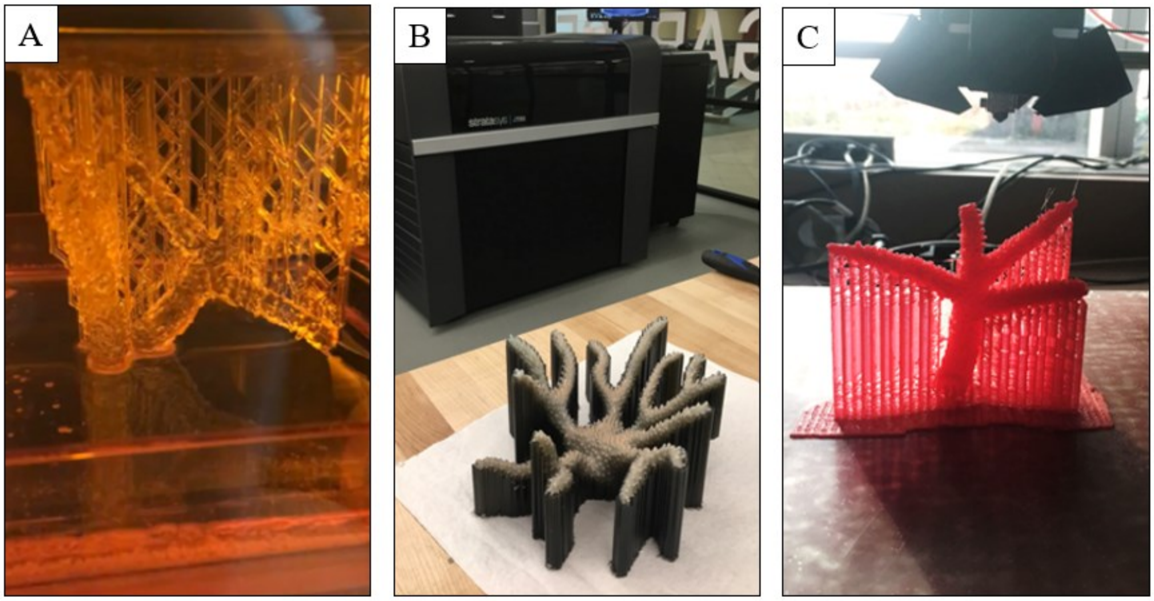

Fig. S1 (A) 3D print from a *Formlabs Form II* resin printer, figure showing high-resolution print quality but limited in cost and availability of printer material (B) 3D printing from a *Stratasys j750* printer, figure showing high-resolution print quality but limited in cost and availability of printer material. (C) A complex 3D print using a basic extrusion-based printer, figure showing more material dedicated towards support material than the print itself.

1.2 Links for online tutorials and 3D model databases

[Tinkercad]

[Thingiverse]

[Ocean Agency coral 3D files]

[Smithsonian 3D Digitization]

2.0 Further description of artificial habitat materials and their relation to accessibility, scalability, and ecology performance attributes in Table 1

2.1 Accessibility

2.1.a Resource availability:

Materials that score highly in terms of resource availability criteria are plastics, biogenic materials, line/nets, metal, rocks/rubble and concrete. Plastics are easily obtainable from commercial retailers in urban centers and thus are widely used to create AHs. Some examples of plastic AHs are PVC plates to enhance larval coral settlement (Oren and Benayahu 1997), PVC pipes to mimic mangrove prop roots (Verweij et al. 2006, Nagelkerken and Faunce 2007; **Fig. 2A & E)** and plastic leaves to imitate *Thalassia testudinum* (turtlegrass) in artificial seagrass beds (Verweij et al. 2006). Biogenic materials score highly as they were some of the first artificial habitats used in artificial habitats (D'itri 2018) due to their wide availability, and are thus still used to date (Ellis and Bell 2004, Walles et al. 2016). 3D prints are explicitly scored separately than Plastics as they can be printed using a variety of materials. 3D prints score moderately as some types of 3D printing material or printing equipment may be more difficult to access. For example, although the capacity to 3D print has increased dramatically over the past few decades (Kumar et al. 2016), printers and printing material are still fairly inaccessible outside commercial retailers in urban centres (Trilsbeck et al. 2019). Ceramics score moderately because although their construction material (clay) is widely available, their main limitations lie in the additional equipment required in post-production processes -like kilns. Additionally, specialized ceramic 3D printers and printing filament may be difficult to access depending on your location and project budget (Lee et al. 2017).

2.1.b Cost:

Materials with highest performance (lowest costs) include biogenic materials (e.g. oyster shells), line/nets (polypropylene line & nylon mesh), metal (stainless-steel mesh and galvanized steel sheet), rocks/rubble and concrete. Rocks and rubble have been favoured due to low costs, or simply used opportunistically at no cost (Lima et al. 2019). Plastics generally have a wide price range, with cheaper plastics often favoured due to their low cost (and associated accessibility) and low training requirements, thus scoring moderately. Materials with highest associated costs (and lowest cost performance) are 3D prints and ceramics. The cost of 3D printing was calculated for material needed to create a solid $1m^3$ block (100% infill) as well as a partially solid block (15% infill) as prints are most often made using a partial infill, greatly reducing material demands and associated costs. 3D printing is the most expensive option, however costs are decreasing as the technology and materials become more available globally (Trilsbeck et al. 2019). The range of printing materials now available to 3D print includes biodegradable plastic, ceramics, and even sandstone (Lee et al. 2017), however these specialized materials increase production and post-processing costs. A growing demand for 3D printing technology has allowed individuals to contract companies or institutions for 3D prints, or to spread the cost of a 3D printer over several modules -thus reducing associated costs. Note that the cost estimates in Table 2 are only those associated with material, and do not include equipment required for construction. Those would also vary depending on design/construction method.

2.1.c Training required:

Most materials score highly as they require little training in the three phases of AH creation (design, construction, and deployment). Plastics, biogenic material, line/nets, metal, rocks/rubble and concrete are readily accessible and come ready-to-use. 3D printing scores moderately as there is a significant time investment in scanning, file manipulation and print supervision needed to ensure high-quality printing (Trilsbeck et al. 2019). The availability of 3D printing resources and training may be more easily overcome at institutions with digital technology centres that have trained staff (Behm et al. 2018). However, once initial investments are made, and 3D files are created, it is a design type that reduces in cost over time as files can be made available on free file-sharing services, and the cost per unit decreases as more modules are printed. These files are also shareable among networks or even globally on file-sharing servers such as thingiverse.com, increasing it's potential to be used by those that don't necessarily have file-creation training or equipment.

2.2. Scalable

2.2.a Durability:

Rocks/rubble, concrete, and ceramics score highest as they are all substances that are relatively stable in aquatic environments (Umar et al. 2015). Concrete in particular is a versatile material that can be used in conjunction with other materials for module stabilization (Nagelkerken and Faunce 2007, Biggs 2013), making it a strong contender for artificial habitat (AH) construction in a variety of shapes, sizes and amalgamations. Plastic, 3D prints, biogenic materials and metal score moderately as certain types or configurations are more durable than others, but more broadly have been shown to break down via wave action and exposure to sunlight (Eriksson and Burton 2003). For example, oyster shells are often used in oyster reef restoration as they are easily accessible and have been found to promote larval oyster recruitment (Nestlerode et al. 2007). However, if the loose shells are not properly amalgamated within a supportive structure, they can quickly scatter or become buried in sediment (Lukens and Selberg 2004), making them less likely to persist in an aquatic environment without degradation (La

Peyre et al. 2014). 3D printing material impacts module durability; typical PLA-printed modules would have lower durability in aquatic environments compared wish high quality, UV bonded polymer material or 3D printed ceramic modules. Lines and nets score poorly as they are most often used in suspension and/or in conjunction with reef balls/concrete blocks (Sherman 2002), making them susceptible to tearing and detachment due to wave action or boat propeller cuts. Note that durability (a modules persistence in the environment) depends on material type but also deployment method).

2.2.b Ease of deployment:

Plastics, biogenic material, rocks, metal, and concrete have high performance under this metric as they are negatively buoyant and depending on the module type need little adhesive material, supports, and personnel to affix to the benthos in aquatic environments. Additionally, AHs deployed using these materials typically don’t take up much volume or weight, making them logistically easier to deploy by wading, vessels and/or scuba divers (i.e fewer personnel and less time needed for deployment). Line and nets score moderately as they are typically positively buoyant material, requiring extra deployment attention to be properly affixed to substrate or to the AH module in use. Concrete also scores as only somewhat meeting this requirement as it is a heavy material, often deployed in large blocks (Moring and Nicholson 1994., Bortone et al. 1994) reef balls (Sherman 2002), or complex modules, making it more resource intensive in volume and personnel capacity to deploy. To conserve printing material and print time, 3D prints are often printed with a hollow or partially hollow infill, resulting in hollow space that makes them positively buoyant, difficult to deploy/affix to bottom substrate and more likely to float away from AH area to become aquatic debris. However, most 3D-printed AHs are small enough that they can be easily affixed by one person, reducing time and effort to deploy, thus score moderately.

2.2.c Ease of Reproduction:

Plastics, line/nets, metal, rocks/rubble and concrete score high as most modules using these materials can be made relatively quickly (i.e. within two weeks). Biogenic material scores moderately as there are finite biogenic resources available for AH creation, potentially limiting the time needed to obtain resources to construct and deploy habitat modules. Ceramics score moderately because they may be limited in terms of the time required to properly dry and kiln-fire ceramic work before deployment.

2.3 Ecology

2.3.a Morphological realism:

Biogenic material and 3D printing have the highest metric performance in this category. The former due to its obvious biogenic origins (**Fig 2C**) and the latter due to its potential as a tool to create highly morphological realistic modules (**Fig 2B**; Mohammed 2016). 3D scanning and printing technology has already been rudimentarily tested in aquatic habitats (Ruhl and Dixson 2019), with the ability to create extremely high-resolution micro-habitat characteristics such as coral polyps on a coral head (**Fig. 3C**). Plastics, line/nets, metal and rock score moderately, as they are often used to create AHs with low morphological similarity to biogenic habitat (Lima et al. 2019) such as simplistic PVC or tile modules (Brotto and Araujo 2001; **Fig. 2A**). Other simplistic modules are often made using concrete. For example, studies using concrete most often deploy them as simple concrete blocks (Talbot 1965, Sherman 2002, Cresson et al. 2019; **Fig. 2H**) or stacked modules (Santos et al. 2011) that have little morphological similarity to biogenic habitat. One must also consider that after a long time, concrete blocks could collapse and damage underlying biogenic benthic habitat. In some cases, metal mesh has been favoured due to its malleability and ability to be manipulated into complex forms. However, this attribute has mainly been used to hold together conglomerate materials like shells/rubble to create modular AHs (Scarcella et al. 2015). Ceramic AHs have been deployed in pyramid tile-modules to test habitat complexity (Brotto and Araujo 2001; **Fig. G**), as simple stand-alone tiles to test benthic assemblage recruitment (Umar et al. 2015), and even created using specialized ceramic 3D printers (Mohammed 2016, Trilsbeck et al. 2019).

2.3.b Chemosensory stimulation:

Rocks/rubble, ceramics and concrete all score with high performance as there is little evidence indicating chemosensory stimulation by secondary organisms. 3D prints score moderately as those made of plastics face the same chemosensory response considerations as other plastics, while those made of ceramic likely have negligible effect. Initial laboratory studies indicate that fish behaviour is not impacted by 3D printed objects (in terms of time spent in 3D printed habitats; Ruhl and Dixson 2019), however we caution that more studies on a diverse assemblage of fish over long periods of time would need to occur to have confidence in deploying 3D printed plastic modules in the field. Line/nets score moderately in this category as their composition and design may vary and influence aquatic organisms differently (i.e. synthetic vs organic fibre lines). Metal also scores moderately due to the variability of metal types and forms employed as AHs. For example, iron ions released during oxidation can actually increase primary productivity in the immediate surroundings (Layman et al. 2016), however the type of metal and its treatment are important considerations as certain compounds may impair physiological and behavioural response in surrounding organisms (Weis et al. 2001, Sovová et al. 2014). Plastics score poorly due to the growing body of evidence linking micro and nano-plastic effects on aquatic species physiology and behaviour through emitted chemosensory stimulation and nano-particle consumption (Wegner et al. 2012, Cedervall et al. 2012). Biogenic material scores as unknown as they may contain cues associated with the once-living organism, potentially confounding study results aiming to disentangle the effect of living organisms and structure on habitat selection. For example, in a study examining larval oyster recruitment to living and artificial oyster reefs, Walles et al. (2016) used bags of living oysters to mimic a natural reef and bags of oyster shells to mimic an artificial reef and found higher oyster larval recruitment at natural reefs. This could be due to the chemosensory ability of larvae to detect chemical cues of conspecifics (Tamburri et al. 2008) or by the soundscape cues associated with living oyster reefs (Lillis et al. 2013), but could also be due to negative habitat cues associated with degraded habitat (Dixson et al. 2014), making it difficult to disentangle which cues are driving a habitat selection response.

2.3.c Environmental Impact:

Biogenic material scores highly as they don't have a degrading effect to the surrounding chemical and physical environment in the short-term. Rocks/rubble, and concrete and ceramics have a similar chemical composition to rocky substrates (Dennis et al. 2018) thus score highly. Ceramics have the potential to reduce epifaunal biofouling in aquatic environments due to material pore-tightening during the firing process. Recently, there has also been increased development in creating "green" concrete and low-carbon concrete for artificial aquatic habitats that use locally available materials and lower carbon emissions during production (Zheng et al 2018). These qualities make concrete and high performance materials for AH construction. 3D prints score moderately as there is growing research and availability of biodegradable printing material, however the break-down process in an aquatic environment still runs the risk of creating harmful marine debris and/or contribute to aquatic microplastic pollution. One of the first 3D printed reefs was made using a specialized 3D printer and patented sandstone printing material (SOI 2012). While this has lower environmental impact, it remains inaccessible and expensive for researchers or restoration managers. Line/nets and metal score moderately as they don't necessarily pose an immediate threat to their local chemical and physical environment from short-term degradation, however if dislodged or unattended, run the risk of being extremely harmful to aquatic and non-aquatic wildlife via entanglement, or bio-accumulation over the long-term (Read et al. 2006, Bergmann et al. 2015). While some plastics have been favoured due to their low toxicity when dissolved in water (Baine 2001, Wolfe and Mumby 2020) or corrosion resistance (Lima et al. 2019), there are many plastics that release chemicals harmful to marine biota (Sherman and Spieler 2006), or breakdown in harsh ocean conditions (Hudson 1993). Furthermore, the deployment of plastics in aquatic environments further contribute to the aquatic plastic pollution crisis (Sigler 2014), making plastics an undesirable material to continue using in AH deployment and why it is ranked poorly.

3.0 Further discussion on using AHs for restoration design purposes:

3.1 *Defining restoration success:*

Restoration "success" is determined by meeting specific restoration goals and thus success metrics vary from project to project. For example, restoration goals using AHs in aquatic ecosystems could be multi-dimensional to include direct benefits such as enhancing settlement surface area, local production, fisheries production,(Miller 2002, Powers et al. 2009) and/or increasing biodiversity (Epstein et al. 2003, France and Duffy 2006). They can also include indirect service-related goals such as water quality and public health concerns(Coen and Luckenbach 2000), anti-trawling deterrents (Jensen et al. 2000), or reflect passive values such as knowledge that habitats are conserved for future generations (Whitmarsh et al. 2008). Restoration success is clearly dependent on the local context, thereby directly dependent on holistic monitoring of pre-defined success metrics (Ruiz-Jaen and Mitchell Aide 2005). A holistic monitoring process includes initial and continued involvement from a variety stake-holder groups that incorporates socio-environmental approaches,(Wortley et al. 2013, Belhassen et al. 2017) a process often overlooked by restoration researchers and/or practitioners.

In addition to monitoring, restoration success may be determined relative to a reference baseline, pre-disturbance information can be established based on historical data and/or indigenous knowledge that surpass records in western science (Koehler 2009, Ens et al. 2012). However, even when controlling for these factors, studies employing AHs don't typically report on the "success" of an AH in meeting any design criteria, as they are often focussed on a particular aspect of using the AH to study a specific phenomenon -such as its ability to promote ecological characteristics like recruitment or biodiversity (Sale 1991, Sherman and Spieler 2006, Powers et al. 2009, Walles et al. 2016, Ruhl and Dixson 2019) enhancing fisheries production (Seaman 2007, Whitmarsh et al. 2008, Beck et al. 2011). The wide variety of purposes, contexts and designs in which AHs are deployed make it difficult to evaluate the performance of AHs in a standardized way (Baine 2001). It is our hope that methods such as the one described in this paper can offer a way to standardize AH comparisons when applied to restoration planning.

3.2 Cautionary Management:

One of the most common uses of artificial structures in aquatic systems is the use of Fish Aggregating Devices (FAD). FADs are structures that heterogenized the pelagic sea-scape to offer water-column aggregation space. They are one of the oldest technologies used by fishermen, with indigenous design, technologies and usage pre-dating the relatively recent interest in FADs for commercial fisheries and western science (Bortone 2006, Raju et al. 2016), where they are most often deployed to enhance fisheries (Castro et al. 2002).While FADs certainly show evidence of aggregating surrounding species, this calls into question whether they are simply attracting species to a novel habitat vs. enhancing the production of the habitat and its surrounding area. The “attraction vs production” debate is a long-standing question of whether artificial structures simply re-distribute already existing species in the area (attraction) or increase an area’s carrying capacity by enhancing juvenile recruitment and retention (production). Two of the biggest cautions of using FADs in habitat selection studies or restoration activities is that they typically fall into the former category of attracting biomass, rather than increasing ecosystem productivity, and when employed simply as a fishing device, FADs may be used to exploit surrounding species (Seaman 2007).

While Artificial habitats serve a unique role in enhancing ecosystem function and resilience, a focus on only habitat replacement may lead to passivity in conservation, over-exploitation of newly attracted species and an over-reliance on technological solutions rather than addressing necessary systematic changes. No number of studies can protect against the chronic effects of climate change, but local action can still make a difference to protect key local species, transfer resilience to ecosystems, and act as a buffer to degradation (Côté and Darling 2010, Bruno et al. 2019) Therefore, we strongly recommend against using 3D-SPMC for wide-scale restoration, rather as a tool to identify important features of habitat and the contexts in which they matter. We recognize that ecosystem restoration is a participatory political process to also repair human-environment relationships which serves to resist the colonial and capitalistic systems which dismantle that relationship (Fox et al. 2017) and contributes further to habitat degradation.

4.0 Supporting Videos

4.1 habitat module assembly video

For a video detailing the habitat module assembly process, please visit:

https://drive.google.com/file/d/1O-lr2haKbyH8R1_ztmy4oG0MPa2tjP1e/view?usp=sharing

4.1 habitat module assembly video.mp4

4.2 habitat module deployment video

For a video capturing a scuba diver deploying the habitat module (consent approved by research assistant Taylor Restall), please visit:

https://drive.google.com/file/d/1Om2u_ZVbcH63LoCR3XUAo4GGP4shkSal/view?usp=sharing

4.2 habitat module deployment video.lv

5.0 Pragmatic considerations for the planning phase:

The following is a set of reflective questions designed for users to consider before using the 3D-SPMC method. It reflects the design process and questions we encountered during the methodology development. The following is divided into 2 parts: Part 1: Project Objectives, and Part 2: 3D-SPMC Steps and Considerations.

Part 1: Project Objectives

1. Identify: what are you using the method for?
    a. Habitat Cue Study
        i. What is the goal of your research?
        i. What response metric will you measure?
        ii. At what scale does this ecological process occur?
        iii. What is the appropriate scale/size of the artificial module that matches that ecological process?
    b. Inform Restoration Design
        i. What is the goal of your Restoration Program?
        ii. How will employing this method provide information on:
            - Optimal design and placement of living or artificial habitats?
            - What percent living biogenic habitat is needed for colonizing organisms to detect and use habitat?
2. Pragmatics:
    a. Site selection:
        i. Where will this project take place? (lab vs field)

ii. How will you access field sites and transport modules there?

iii. Depending on size of final module: does it need to be modularized and built in-situ? How will they be affixed? Plan placement.

b. Collaborators & Resources:

i. Who has similar goals to yours, or is already working on something similar?

ii. What kind of time/resources are at their disposal already?

c. Time & Money:

i. What is your project budget?

ii. What is the time-scale of your project? How man modules will you need to make in that time frame? (taking into account the time needed for printing, and drying in the mould making and casting steps)

iii. What is the minimum unit of replications for your project (including extras in case any break) and do they fit the time and budget parameters?

d. Space:

i. Do you have a reliably dry work space for the moulding and casting stages?

ii. Is there somewhere to store concrete casts while they are curing?

iii. Where will casts be pre-soaked prior to deployment?

<u>Part 2: 3D-SPMC Steps and Considerations:</u>

1. Scanning & Virtual Augmentation:

   a. Are there already 3D files available on any of the 3D file databases? Check:

i. Tinkercad, Thingiverse, Pinshape

ii. Coral specific: Coral image bank, Smithsonian coral database

b. Do you need to edit the file to meet your needs? If so, some of the common 3D editing softwares are:

i. freeCAD, Microsoft 3D Builder, Meshlab, Tinkercad

*note: on some databases you can filter objects by shape and file type. Depending what kind of 3D editing software available to you, this may be necessary

ii. Check what software your own institution, collaborators, colleagues already have access to.

iii. Are there easily accessible tutorials for the software you want to use?

iv. Are there digital educators you can consult (i.e. digital scholarship libraries, engineering maker-spaces, 3D design contractors

*note: when it comes to 3D models, there are many ways to skin the cat. Depending on your proficiency with learning new softwards, the time you have to learn a new technique, often seeing what the people around you already use and have access to is a good choice.

2. 3D Printing:

a. Printing Resources

i. Which printers are available to use? Good places to start: engineering faculties, libraries (public or institutional), research labs that do re-constructive morphology (medical, paleontological).

ii. Depending on your budget, you may be able to out-source the printing to a 3D printing contractor. These private businesses are becoming more popular, and may even be able to help during the design phase.

b. Printer considerations

i. What is the print area of the "build plate" (the area the print is being printed onto) and the volume of the area you can print?

ii. If you require a bigger module than the build area/volume, you may need to go back to Step 1 and modularize your 3D file into components that can be assembled post-printing or post-casting

iii. What kind of printing material are you using? What size of filament is compatible with your 3D printer?

iv. What kind of infill will you need for your print? (0-100%)? In the 3D-SPMC method you likely don't need a solid object (this saves on printing material and printing time) We recommend looking at the different print options for the printer in use and using a lower infill (0-15%).

v. How many 3D files can you upload to the build plate? For small 3D files or large build plates, you may be able to fit more than 1 3D file on the build plate. This may slightly increase the print time, but it is a more efficient way of reproducing numerous 3D prints at once.

*note: Again, there are many printers now available on the market, with a variety of printing techniques. If you are new to this, we recommend consulting with experts who have already done this. Even though it is a relatively simple process when you get used to it, there will inevitably be trouble-shooting involved once you begin.

3. Mould Making:
    a. Mould material
        i. How many times do you want to re-use your flexible mould? We recommend *Dragon Skin Silicone* moulding material for its longevity and high-resolution capture of fine-scale details, but there are other options available: silicone from caulking and dish soap, silicone from caulking and cornstarch. (Keep in mind that often these lower-budget moulds may be best suited for proto-typing but may not withhold multiple casts, nor be flexible enough to capture fine-scale details.)
    b. Mould design
        i. What shape is your 3D-print? Can you orient many prints in a planar area? How you orient the 3D prints on the moulding surface will represent a trade-off between conserving moulding material and leaving enough space between casts that you don't damage them in the removal process.
        ii. Depending on the final module shape, you may decide to place the 3D print flush on the moulding surface, or use clay to lift the 3D print to create a small gap.

4. Casting
    a. Material
        i. Depending on your research questions/module size, we recommend proto-typing your cast to see how they look and withstand underwater. Other considerations: At what depth will they be deployed; how will that affect colour attenuation? Is it a turbid environment; does colour not matter as much?
        ii. Mould release is sold as a specific product (by *Viking plastics* and other companies. In our experience and consultations, a neutral vegetable oil is a far cheaper and more effective alternative. *Be sure to pre-soak your modules pre-deployment to release any cues associated with the mould release and casting materials*
    b. Space
        i. Do you have a covered/dry area to process the casts and let them dry fully? Concrete becomes stronger over time as it cures -the longer you let the modules cure pre-deployment the better (particularly for high wave action/current locations)
        ii. Even though it’s not necessary, having fans blowing at a low, slow speed over casts will help dry faster (particularly in humid environments)

5. Assembly & Deployment
    a. Assembly

i. How complex are the modules? Do they need multiple attachment points?

ii. If designed to be modularizable, can the modules be designed to "inter-lock" to conserve attachment material? (i.e. create locking points in the design stage)

iii. Other forms of attachment to consider in the assembly phase: concrete, cement, ceramic that's then fired.

b. Deployment

c. How much does each module weight? When taking into account replication, will all modules be able to be transported at once?

d. If modular, what is the final weight/volume of the module? Does it make sense to transport the module fully constructed or in parts?

*note: Keep in mind your study objectives; is there a way to deploy modules that mimic biogenic habitats or restoration efforts in your study area? (i.e. some coral restoration practitioners affix coral fragments to the benthos with nails and zip-ties vs. *epoxy*)

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