FACULTY OF ENVIRONMENTAL PROTECTION

MASTER'S THESIS

SUSTAINABLE 3D-PRINTING TECHNOLOGY IN MARINE AND URBAN ECOSYSTEM RESTORATION

PIA CVERLIN

VELENJE, 2025

FAKULTETA ZA VARSTVO OKOLJA
FACULTY OF ENVIRONMENTAL PROTECTION

MAGISTRSKO DELO

TRAJNOSTNA TEHNOLOGIJA 3D-TISKANJA ZA OBNOVO MORSKIH IN URBANIH EKOSISTEMOV

MASTER'S THESIS

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PIA CVERLIN
Varstvo okolja in ekotehnologije
Environmental protection and Eco-tehnologies

Mentorica / mentor: doc. dr. Tanja Tajnik
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VELENJE, 2025

FAKULTETA ZA VARSTVO OKOLJA

Številka: 727-1/2024-2
Datum: 25. 4. 2024

Na podlagi Diplomskega reda izdajam naslednji

SKLEP O MAGISTRSKEM DELU

Študentka Fakultete za varstvo okolja **Pia Cverlin** lahko izdela magistrsko delo z naslovom v slovenskem jeziku:
Trajnostna tehnologija 3D - tiskanja za obnovo morskih in urbanih ekosistemov

Naslov magistrskega dela v angleškem jeziku:
Sustainable 3D - Printing Technology in Marine and Urban Ecosystem Restoration

Mentorica: **doc. dr. Tanja Tajnik**
Somentorja: **dr. Pierre Oskam in Nadia Fani**

Magistrsko delo mora biti izdelano v skladu z Diplomskim redom.

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Document No.: 727-1/2024-2
Date: 25th April 2024

Based on the Graduation policy of the Faculty of Environmental Protection, the faculty issues the following

DECISION ON MASTER'S THESIS

Student **Pia Cverlin** of Faculty of Environmental Protection is entitled to write a master's thesis, which in Slovenian, is titled:
Trajnostna tehnologija 3D - tiskanja za obnovo morskih in urbanih ekosistemov

The title of the master's thesis in the English language:
Sustainable 3D - Printing Technology in Marine and Urban Ecosystem Restoration

Supervisor: **Tanja Tajnik, Ph.D., Assist.**
Co-supervisor: **Ph.D. Pierre Oskam and Nadia Fani**

The master's thesis shall be written and structured in compliance with the Graduation policy.

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Podpisani/a Pia Cverlin, vpisna številka 34220024,
študent/ka podiplomskega študijskega programa Varstvo okolja in ekotehnologije,
sem avtor/ica magistrskega dela z naslovom

Trajnostna tehnologija 3D-tiskanja za obnovo morskih in urbanih ekosistemov

(Sustainable 3D-Printing Technology in Marine and Urban Ecosystem Restoration),

ki sem ga izdelal/a pod:

- mentorstvom doc. dr. Tanje Tajnik
- somentorstvom dr. Pierra Oskama in Nadie Fani.

S svojim podpisom zagotavljam, da:

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Podpis avtorja/ice: Cverlin

ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisor, doc. dr. Tanja Tajnik, for her guidance and support throughout this research. I would also like to thank my co-supervisors, dr. Pierre Oskam and Nadia Fani, for their expertise, constructive feedback, and the data they generously shared, which were essential for the success of this research.

Last but not least, I would like to thank my family and partner for their support and patience. Without them, none of this would be possible.

IZVLEČEK

Magistrsko delo raziskuje potencial 3D-tiskanja kot orodja za obnovo morskih in urbanih ekosistemov z izkoriščanjem njegove sposobnosti ustvarjanja kompleksnih in prilagodljivih struktur iz širokega nabora materialov. Zaradi nedavnega povečanja priljubljenosti aditivne proizvodnje je vrednotenje s stališča trajnosti ključnega pomena.

Prvi del vključuje podroben pregled literature aditivne proizvodnje, njene porabe energije, trajnosti filamentnih materialov ter oceno obnovitvenih projektov morskih in urbanih ekosistemov. Delo ugotavlja, da je izbira trajnostnih materialov ključnega pomena, doseže pa se lahko z natančno analizo življenjskega cikla (LCA), medtem ko izbira energetsko učinkovite metode tiskanja igra ključno vlogo pri zmanjševanju okoljskega vpliva. Celovita ocena trajnosti pa bi morala vsebovati tudi analizo cenitve stroškov celotnega življenjskega kroga (LCC) in oceno socialnega življenjskega cikla (SLCA).
Ključni parametri za optimalne strukture in obnovitvene projekte so bili identificirani kot strukturna kompleksnost, material substrata in morfologija površine.

Drugi del predstavi študije primera dveh okoljskih startupov – Coastruction in Urban Reef. Prvi ustvarja 3D-tiskane strukture za obnovo morskih ekosistemov, medtem ko drugi razvija 3D-tiskane bioreceptivne strukture za obnovo urbanih območij.
Študiji primerov sta pokazali, da sta obe podjetji primer dobre prakse uporabe 3D-tiskanja za obnovitev ekosistemov, hkrati pa so bili s pomočjo študij identificirani ključni parametri in smernice za uspešno umestitev takšnih projektov.

Rezultati dela podpirajo uporabo 3D-tiskanja za obnovo morskih in urbanih ekosistemov, vendar je potrebno upoštevati energetsko učinkovitost tiskanja, trajnost izbranih materialov in toksičnost materialov za okolje, da lahko zagotovimo trajnost tehnologije in preprečimo negativen ekološki vpliv. Aditivna proizvodnja omogoča ustvarjanje prilagodljivih kompleksnih struktur iz naravnih materialov z visoko kompleksnostjo strukture in idealno morfologijo površine, ki sta bili identificirani kot ključna parametra za uspeh obnovitvenih projektov. Temeljito eksperimentiranje in raziskovanje sta prav tako ključnega pomena; multidisciplinarno sodelovanje z raziskovalci in strokovnjaki lahko zagotovi še boljše rezultate in ciljanje specifičnih vrst.

Ključne besede: 3D-tiskanje, trajnost, obnova, rehabilitacija, morski ekosistem, urbani ekosistem.

ABSTRACT

This thesis explores the potential of 3D-printing as a tool for marine and urban ecosystem restoration by utilizing its ability to create complex customizable structures from a large variety of materials. Due to the recent increase in additive manufacturing popularity, an evaluation of its sustainability was necessary.

The first part of the thesis includes a thorough literature review of additive manufacturing, its energy consumption, and filament material sustainability, as well as an evaluation of marine and urban ecosystem restoration efforts. It concludes that sustainable material selection is crucial and can be partially achieved by performing a detailed Life Cycle Assessment. However, a comprehensive sustainability evaluation should also include Life Cycle Costing and Social Life Cycle Assessment. Additionally the choice of an energy-efficient printing method also plays a vital role in reducing the environmental impact.
Key parameters of optimal structures in restoration projects were identified to be structure complexity, substrate material, and surface morphology.

The second part of the thesis presents case studies of two environmental start-ups – Coastruction and Urban Reef. The first is creating 3D-printed structures for restoring marine environments, while the second is developing 3D-printed bioreceptive structures for restoring urban environments.
Case studies identified that both companies are an example of best practices in applying 3D-printing for restoration efforts, while also providing essential parameters and guidelines for the success of such projects.

Results of the thesis support the use of 3D-printing for marine and urban ecosystem restoration but energy efficiency, material sustainability, and environmental toxicity must be addressed to ensure its sustainability and prevent a negative ecological impact.
Additive manufacturing allows the creation of customizable complex structures from natural materials with high structure complexity and ideal surface morphology, which were identified as key parameters for success in restoration efforts. Thorough experimentation and research are crucial where inter-disciplinary collaboration with researchers and experts can ensure even better results and even targeting of specific species.

Keywords: 3D-printing, sustainability, restoration, rehabilitation, marine ecosystem, urban ecosystem.

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ACRONYMS

CAD	Computer-Aided Design
STL	Stereolithography
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
PLA	Polylactic Acid
CNC	Computer Numerical Control
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
SLCA	Social Life Cycle Assessment
ISO	International Organization for Standardization
CCP	Calcium Carbonate Photoinitiated Ink
CCA	Crustose Coraline Algae
EPA	Environmental Protection Agency
DIY	Do It Yourself
ReCiPe	A Method for Impact Assessment in LCA
RAC	Recycled Concrete Aggregate

1 Introduction

Marine ecosystems, specifically coastal habitats like coral reefs, mangroves, seagrass, and oyster reefs, provide food and biotic materials, coastal protection, and even cultural services (tourism). Thousands of coastal communities depend on them for food and work, yet they are being increasingly degraded and transformed by mostly anthropogenic impacts. Over just a few decades, global mangrove coverage has declined by more than 35% and coral reef coverage by 19%. (Bayraktarov et al., 2016)

Meanwhile, urban ecosystems face their challenges. Urbanization has caused the loss of native species and biodiversity but interest in urban greenspace has increased in the past decades, largely due to its importance for wildlife conservation, human welfare, and climate change adaptation. (Klaus & Kiehl, 2021)

As both of these ecosystems are incredibly important for humans, the number of restoration projects and ideas has been gradually increasing over the past decades. From artificial reefs to green roofs, we are experimenting and developing solutions to stop and repair degraded areas.

Additive manufacturing, specifically 3D-printing, has been revolutionary and is now available for every consumer. Its ability to create complex objects with almost any material has shown promising results in numerous industries like manufacturing, biomedicine, and even ecology. Multiple restoration projects have started experimenting with 3D-printed custom solutions, creating shapes that were previously impossible or too expensive.

However, the sustainability of 3D-printing technology should be carefully evaluated to ensure it does not have a secondary negative environmental impact. Forming guidelines for future projects is crucial because it will ensure an environmentally friendly approach to restoration efforts.

1.1 Purpose

Evaluate the impact of 3D-printed solutions on the biodiversity of marine and urban ecosystems.

Assess the ecological impact of 3D-printed solutions.

Prepare guidelines for the development of environmentally friendly and sustainable 3D-printed solutions for the restoration of marine and urban ecosystems.

Identify key parameters that influence the suitability of 3D-printed solutions in marine and urban ecosystems.

1.2 Research Questions and Hypotheses

Research questions

What impact do 3D-printed solutions for the restoration of marine and urban ecosystems have on biodiversity?

What general ecological impact do 3D-printed solutions for the restoration of marine and urban ecosystems have?

How can we ensure that 3D-printed solutions for the restoration of marine and terrestrial ecosystems are sustainable, environmentally friendly, and best utilized?

Hypotheses

H1: 3D-printed solutions show a higher recruitment of marine organisms compared to conventional solutions

H2: 3D-printed solutions increase biodiversity in urban areas.

H3: Natural or recycled 3D-printing materials have a lower environmental impact compared to conventional polymer filaments

1.3 Methodology

The thesis adopts a qualitative and theoretical approach, using secondary data sources on the topic of 3D-printing technology in ecosystem restoration. The thesis will be divided into two parts:

1. Literature review.
2. Case studies, comparison, and data analysis.

It is important to note that this thesis is based entirely on desk-based research and secondary sources. No direct biological monitoring or experimental fieldwork was conducted.

Literature review

The first part of the thesis involves a thorough literature review, ranging from an overview of 3D printing technology and materials to marine and urban ecosystem restoration. The focus of the review will be on the sustainability and environmental impact of different technologies and approaches, as well as the evaluation of their success.
This part will lay the foundation for case studies in the second half of the thesis.

Case studies

The second part of the thesis focuses on two case studies, which are an example of marine and urban ecosystem restoration approaches using 3D-printing technology:

1. **Marine ecosystem restoration:** This case study analyzes Coastruction – an environmental startup from the Netherlands. The study revolves around their technological approach to 3D-printing, the use of materials, and challenges.
2. **Urban ecosystem restoration:** The second case study reviews Urban Reef, also an environmental startup from the Netherlands. The company and its approach are evaluated similarly to the first case study.

Case studies were selected due to the relevant approach of using 3D-printing technology, and also because they incorporate sustainable practices in mind when creating the structures and follow current best practices suggested for such applications.

The case studies were selected based on their relevant use of 3D-printing technology, as well as their incorporation of sustainable practices in the design and construction of the structures. Both companies follow current best practices recommended for such applications, making them suitable examples to explore the environmental and technological implications of sustainable 3D-printed restoration efforts.

Special emphasis will be on material analysis and comparison, and 3D-printing processes. These will all be evaluated from an ecological perspective.

The final section of the thesis contains a comparative analysis of both literature review and case studies. As a result, guidelines and recommendations for future research and implementation of 3D-printed restoration efforts will be formed.

2 3D-Printing

3D-printing is a form of digital fabrication technology, which utilizes the power of additive manufacturing. It is becoming an increasingly popular technology for creating physical objects from geometrical representation, layer by layer, depositing various materials. This chapter will cover the basics of 3D-printing technologies and assess them from an ecological standpoint.

2.1 Technology

3D-printing starts with computer-aided design (CAD) models, which are digital representations of real objects. These models are a blueprint for creating physical copies of the objects. There are numerous methods and approaches how to print models but according to ASTM Standard F2792, we can separate them into seven main independent groups or types (Shahrubudin, Lee, & Ramlan, 2019):

- Binder jetting.
- Directed energy disposition.
- Materials extrusion.
- Material jetting.
- Powder bed fusion.
- Sheet lamination.
- Vat photopolymerization.

Different approaches support different materials and also applications. Therefore, each group has a specific purpose. This thesis will focus on two types – binder jetting and materials extrusion – because they are the most relevant for this thesis.
It is important to note, that each type encompasses multiple technologies. For example, this thesis will focus on FDM and clay-based extrusion technologies, which both fall under the material extrusion type.

Binder Jetting

Binder jetting is a popular approach to 3D-printing where a liquid binding agent is selectively deposited to join powder particles. The binding agent is normally a chemical binder that binds the particles and forms a layer. Its advantage is the ability to create large-scale complex structures rapidly. It is widely used for printing with metals, sands, polymers, hybrids, and ceramics. (Mostafaei et al., 2021)

There are five steps to creating an object with binder jetting technology.
First, a 3D CAD model of an object is »sliced« into thin layers and saved as a stereolithography (STL) file. Then, a thin layer of powder is rolled onto the build area. Next, a binding agent is jetted onto the powdered layer. The newly bound powder is then passed by an electrical heater, which partially cures/dries the newly formed object layer. Lastly, the build area is lower by the defined parameter and the steps repeat.
Some binding technologies also require an additional step – curing. It is very common to move the build area to an oven to complete the curing process before removing the structure from the powder. (Mostafaei et al., 2021)

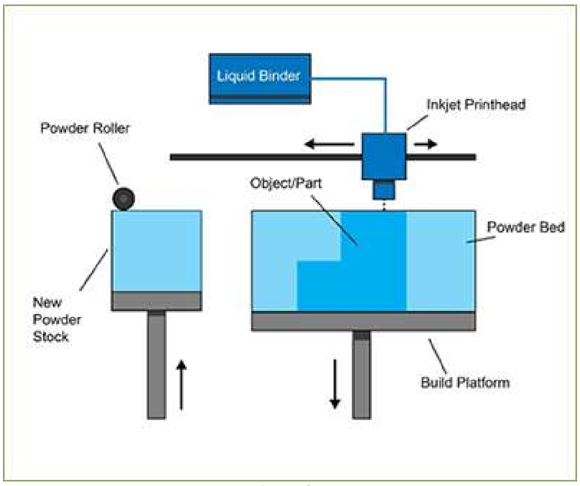

Image 1: Binder jetting
(source: https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/binderjetting/)

Materials Extrusion

Materials extrusion is one of the most popular technologies for 3D-printing in industrial settings, as well as in amateur. There are various subcategories (technologies) to this approach but fused deposition modeling (FDM) or fused filament fabrication (FFF) dominates the field. (Shahrubudin, Lee, & Ramlan, 2019)

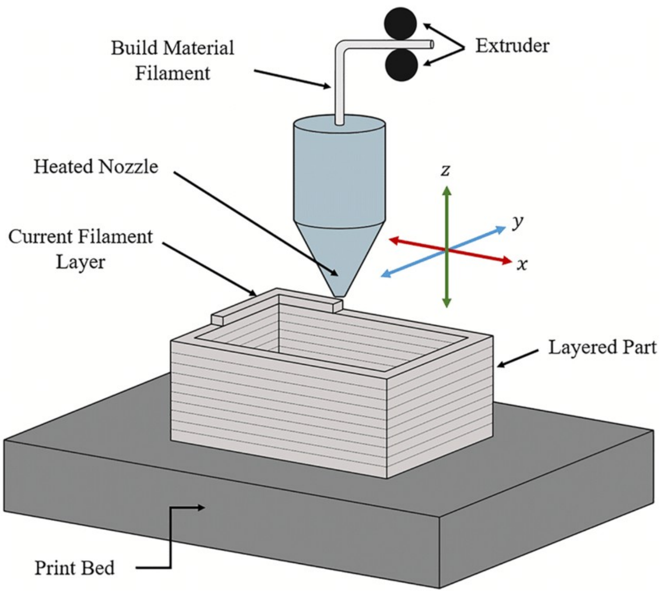

Image 2: Materials extrusion
(source: https://www.researchgate.net/figure/Basic-working-principle-of-material-extrusion-printing_fig1_334546324)

The technology behind FDM printing is very straightforward as we can see in the image above (see Image 2). As in the binder jetting approach, we start with a CAD model that has to be sliced and saved as an STL file. The printer then starts printing the first layer where it usually extrudes the filament through the heated nozzle onto the build area. The nozzle can move in all three degrees of freedom.
The most widespread materials used in FDM printing are polymers, such as thermoplastics and polylactic acids (PLA). While plastics are the most popular, there is growing demand, development, and research of other materials that are also being increasingly used, such as wood, nylon, metals, carbon fiber, biomaterials, ceramics, and concrete. (Mwema & Akinlabi, 2020)

Certain materials do not require a heated nozzle, such as ceramics and concrete. These materials are printed in the same way as plastics, by adding one layer on top of the previous, forming the final structure. They often need after-treatment of curing and/or drying, similar to the binder jetting technology.

The cause for the wide adoption of 3D-printing is its ability to maintain a low cost of production while still allowing the production of small series and personalized items. There is no need for creating molds and additional tools. The only things needed are filament, a 3D-printer, and a CAD model. (Kristiawan, Imaduddin, Ariawan, & Arifin, 2021)

However, it is important to keep in mind that large-scale custom printers are complicated and time-consuming to make and require specific knowledge and skills to create state-of-the-art devices.

2.2 Sustainability and Environmental Impact of 3D-Printing

One of the largest advantages of 3D-printing, which positively impacts the environment, is lowered material wastage. Since there is no cutting and machining, almost 100% of the material used ends up in the final product. This drastically improves the efficiency in manufacturing, significantly lowering materials waste in all of the mentioned groups in Chapter 2.1.
Additionally, there is almost no need for auxiliary resources (tools, jigs, fixtures ...), which again improves the efficiency and lowers the need for production of additional tools. (Mwema & Akinlabi, 2020)

DIY printing at home with small-scale machines was found to be an effective way to upcycle and recycle in minimal ways. It allows users to repair things, eliminating the need to dispose of them, buy new ones, or order spare parts. These all contribute to the lower need for transportation and packaging, positively impacting the environment, by lowering the air and plastic pollution. (Liu, Jiang, Zhang, Li, & Zhang, 2016)

Sometimes, 3D-printed complex shapes need support in the form of additional plastic that is later cut from the final objects. This waste can be fully recycled into raw material that can be used once again for 3D-printing.
Compared to traditional CNC manufacturing, this is a huge improvement. CNC parts are manufactured from a single block of material, which is usually significantly larger. The ratio between the final part and the wasted materials can reach up to 19:1.
When comparing the recycling of traditionally manufactured polymer parts and 3D-printed ones, the latter are much easier to recycle because most of them are printed from a single polymer. Recycling waste is much easier when only one polymer is present, compared to when waste contains multiple. (Liu, Jiang, Zhang, Li, & Zhang, 2016)

When assessing manufacturing methods, a special focus should be put on energy consumption. While recycling the waste material from printing parts does consume additional energy required for recycling, some researchers argue that 3D-printing releases less carbon dioxide from energy consumption than traditional manufacturing. Cumulative energy consumption of polymer parts manufacturing can be reduced by 41-64% with existing 3D-printers today.
However, numerous researchers argue that at the mass manufacturing scale, 3D-printing has a far higher energy impact than traditional injection molding. They are estimating that to create an object of the same weight, the 3D-printing process consumes 50-100 times more electrical energy than injection molding. (Liu, Jiang, Zhang, Li, & Zhang, 2016)

Another research (Shuaib, Haleem, Kumar, & Javaid, 2021) found that additive manufacturing energy consumption is higher than that of subtractive manufacturing. The difference grows with the complexity of the final product. Authors propose that traditional manufacturing is more appropriate when producing large volumes of parts but 3D-printing should be used for customized production.

In traditional manufacturing, a method of subtractive machining is still widely used today (particularly in CNC manufacturing). It involves cutting a single block of material to produce a much smaller end product. When cutting, a cooling liquid is needed. These fluids are called cutting fluids and are complex. When disregarded, they lead to the pollution of terrestrial, aquatic, and atmospheric systems. Additionally, they are a warehouse of fungi and bacteria, not only causing environmental but also health hazards. Some researchers also found evidence that these fluids could lead to skin cancer. (Shuaib, Haleem, Kumar, & Javaid, 2021)

However, there is a proven negative effect of 3D-printing technologies. The most widely spread filaments used are polymers and researchers. Zhang et al. (2019) have found that the effects of particle emissions from polylactic acid and acrylonitrile butadiene styrene, which are the most widely used filaments, are not benign and the exposure should be minimized.

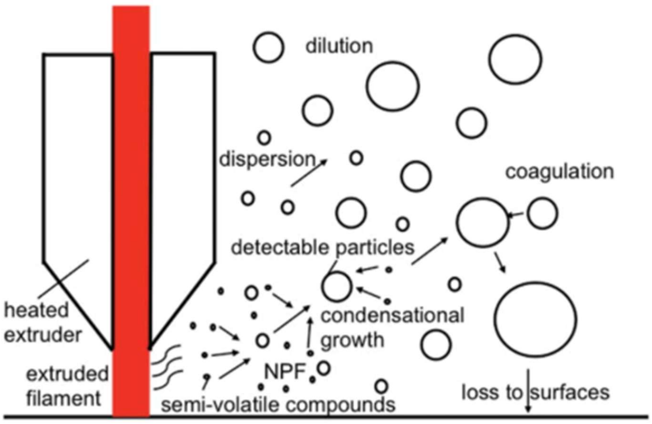

Image 3: Particle formation
(source: Zhang, Wong, Davis, Black & Weber, 2017)

Another research (Zhang, Wong, Davis, Black & Weber, 2017) measured that 20-40 nm particles are consistently emitted when using acrylonitrile butadiene styrene filament. They were present at concentrations up to $10^6/cm^3$. It concluded that the general public can be exposed to high concentrations of nanoparticles of potential toxicity.

Research from 2023 (Fonseca, Ramalho, Gouveia, Figueiredo, & Nunes, 2023) did a thorough Life Cycle Assessment (LCA) of polylactic acid as a biodegradable raw material since it is made from corn starch. It is the most widely used plastic in amateur FDM 3D-printers today, largely due to its low melting point and high strength.
Due to its biodegradable nature, it is often presented as an environmentally friendly choice of plastic. However, only a detailed LCA can provide enough insights to decide whether a material or process is environmentally friendly and sustainable.

However, the biodegradability of PLA in a natural environment is very slow and poses an environmental risk. PLA is usually only efficiently composted under industrial conditions, including high heat and humidity (or a chemical process), where water and carbon dioxide are by-products. Furthermore, after two cycles of reprocessing, PLA is no longer suitable for 3D-printing due to material deterioration. (McKeown & Jones, 2020)

Life Cycle Assessment

LCA is a methodology developed in the 1990s but later formalized by the International Organization for Standardization (ISO). It is an important method for obtaining a thorough assessment of a product or process. It includes all aspects from development to the strategic planning of all operations involved. It provides us with data on the ultimate environmental sustainability of products and processes. (Fonseca, Ramalho, Gouveia, Figueiredo, & Nunes, 2023)

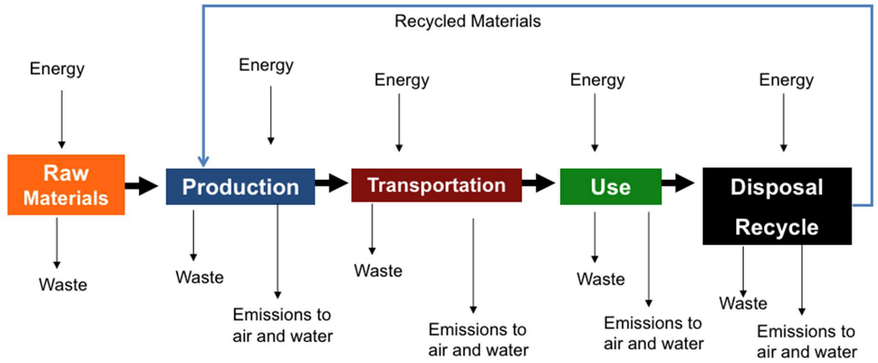

Image 4: Life Cycle Assessment Stages
(source: Venditti, Forest Biomaterials, North Carolina State University, n.d.)

By ISO standards ISO 14040:2006 and ISO 14044:2006, LCA can be divided into four steps:
1. Goal and scope definition.
2. Life Cycle Inventory.
3. Life Cycle Impact Assessment.
4. Life Cycle Interpretation.

These steps outline the research and approach required for a successful LCA. The main takeaways are *data collection on material and energy flows throughout the entire lifecycle* (raw materials, energy inputs, land use, air emissions, water pollution, and land pollution), *data evaluation* (carbon footprint, water footprint, eutrophication, acidification, and human toxicity), *results interpretation.*

The results of correct and successful LCA can lead to making decisions in the industry, such as strategic planning, product design, and also process change. Additionally, it has great importance in leading marketing teams about environmental product claims and ecological labels. (Fonseca, Ramalho, Gouveia, Figueiredo, & Nunes, 2023)

<u>LCA of PLA</u>

Researchers (Fonseca, Ramalho, Gouveia, Figueiredo, & Nunes, 2023) did a detailed evaluation of the life cycle assessment done on PLA products from 2003 to 2023 where a total of 81 papers were analyzed. The impacts of PLA on the environment were compared to other fossil-based plastics (PP, PET, HDPE, LDPE, and PS). Results from multiple articles were normalized to 1 kg of used material.
PLA presented the highest environmental impact amongst all studied plastics in marine eutrophication, freshwater eutrophication, and human toxicity while its climate change impact was the second highest (after PET).

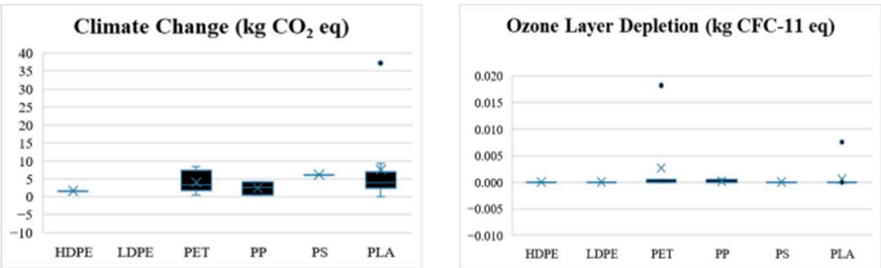

Image 5: Boxplots climate change and ozone depletion
(source: Fonseca, Ramalho, Gouveia, Figueiredo, & Nunes, 2023)

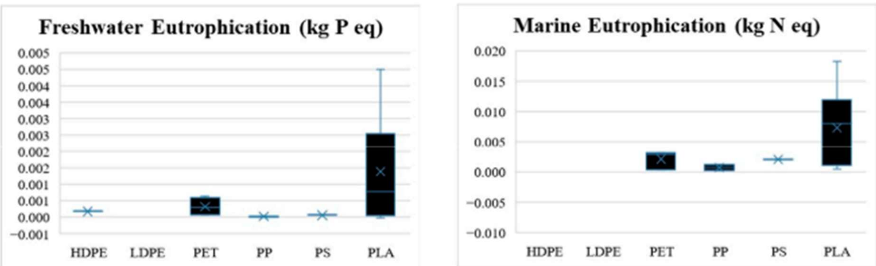

Image 6: Boxplots eutrophication
(source: Fonseca, Ramalho, Gouveia, Figueiredo, & Nunes, 2023)

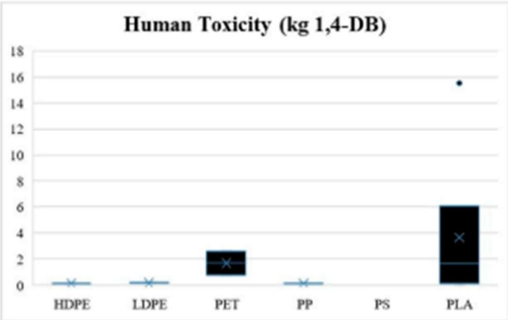

Image 7: Boxplots toxicity
(source: Fonseca, Ramalho, Gouveia, Figueiredo, & Nunes, 2023)

Interestingly, the highest environmental impact of PLA was mostly due to its bio-based nature. Producing PLA from corn and sugar cane has vast agricultural requirements, demanding the production and use of fertilizers, and other agricultural activities, which all contribute to its highly negative impact on the environment. (Fonseca, Ramalho, Gouveia, Figueiredo, & Nunes, 2023)

While this research did not focus on the use of PLA in 3D-printing, the results are important from an environmental standpoint, showing that PLA might not be as environmentally friendly as some claim since it contributes to climate change, freshwater eutrophication, marine eutrophication, and is toxic to humans.

Research provides a solid foundation and direction that detailed environmental assessment of all materials used in 3D-printing should be made, ideally following the LCA principle when searching for those that are appropriate for sustainable use in 3D-printing. Every material must be re-evaluated from its raw production to the final form (filament) to justify and label it as environmentally friendly and sustainable.

It is important to also note that true sustainability also includes **social** and **economic** aspects, which are evaluated through Life Cycle Costing (LCC) and Social Life Cycle Assessment (SCLA). (Guyen Luu & Halog, 2016)
However, this thesis focuses solely on the **environmental** aspect of sustainability through LCA.

2.3 Environmentally Friendly 3D-Printing Materials

In previous chapters, we observed the importance of life cycle assessment in evaluating the true sustainability of materials in 3D-printing.

In the previous chapter, various research articles were presented on the topic of sustainability of typical polymer-based 3D-printing technologies. While researchers today still have not come to a consensus on the environmental impacts of this rapidly developing technology, we can conclude that the analysis of research papers revealed several fundamental aspects that need further exploration – **energy use** and **material sustainability**.

While these seem separate aspects, they are also connected. Energy consumption can be evaluated based on the consumption by the printer in use but it can also be evaluated based on the energy needed to produce a usable filament for 3D-printing. If we conduct an LCA analysis, this can be further extended. The largest connection between filament choice and energy use can be seen when we look at the entire process the material needs to become useful. Many materials (polymer-based) need to be extruded at a high temperature while others might not need high temperature when extruding but need to be cured in the after-process.

An interesting research paper (Rett, Yannick Leandre Traore, & Ho, 2021) focused on sustainable materials for FDM 3D-printing applications. It compared traditional polymer-based 3D-printing to cellulose-based materials as a sustainable alternative. What stands out is that the paper evaluated these materials based on the temperature needed when printing, either when extruding or when curing.

Table 1: Polymer melting properties
(source: Rett, Yannick Leandre Traore, & Ho, 2021)

Material	**Melting temperature [°C]**
ABS, extruded	177-320
PLA, extruded	205
Nylon-6, extruded	216-300
Nylon-6, recycled	260
Polycarbonate, extruded	250-343

In the table above (see Table 1), we can see that the melting temperatures of typical polymers used in 3D-printing are quite high. This means that 3D-printers require large amounts of electricity to heat the nozzle to the desired temperature. Alternatively, cellulose-based filaments do not require heated extrusion but do need some form of curing afterward.
Some can only be subject to a lengthy evaporation process (sometimes even two weeks) while others might require drying at a moderate temperature for a couple of hours to a couple of days.

Table 2: Solidifying cellulose-based materials
(source: Rett, Yannick Leandre Traore, & Ho, 2021)

Material	**Solidification method**
Cellulose acetate/ acetic acid (30/70)	Solvent evaporation
Acetoxypropyl cellulose/ acetone (80/20)	Solvent evaporation
Spruce wooden Chips/ binding agents	Aerosolized water as an activator
Beechwood powder/PVAc (17.5/82.5, 20/80)	Drying (80 °C, 2 h)

Beechwood powder/UF (15/85, 17.5/82.5)	Drying (80 °C, 2 h)
Ground beech sawdust/ methyl cellulose (90/10)	Drying (60 °C, 5 days)

While some cellulose-based filaments only require basic solvent evaporation and therefore much lower energy needs, they are inferior to their plastic counterparts in material properties and not suitable for replacement in the industry.
However, the focus of this chapter is not to look for industry replacements for polymer-based filaments but to discover which printing materials are sustainable and what properties they have. So far, based on research, we can conclude that to find environmentally friendly and sustainable materials, they should have the following:

1. **no toxicity (environmental or human),**
2. **low or no need for high extrusion temperature,**
3. **energy-efficient curing process,**
4. **sustainable material production.**

Some of the conclusions above – low toxicity, low extrusion temperature, and sustainable material production – were the focus of an interesting article (Faludi, Van, Shi, Bower & Brooks, 2019) which also focused on LCA analysis of certain novel materials based on previous research. Researchers agreed that the largest environmental impact was by the energy used during the printing process, which led them to test specific materials that could drastically lower it.

Researchers decided to tackle the issue of low-energy printing by selecting materials that bond or solidify at room temperature and pressure. They also focus on using compostable non-toxic biomaterials for a circular economy (like agricultural waste). This specific research stands out because it did not only look for sustainable materials but also for ones that could mimic mechanical properties, high finish, and low-cost polymer-based filaments.

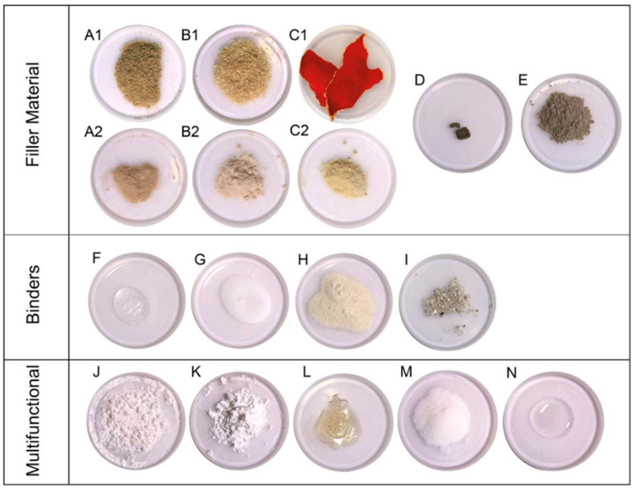

Image 8: Novel material ingredients
(source: Faludi, Van, Shi, Bower, & Brooks, 2019)

The above image shows ingredients researchers used to test their applications. In the first row, there are filler materials: oak sawdust (A1, A2), pine sawdust (B1, B2), orange peel – whole and powdered (C1, C2), dried nanocellulose fibrils (D), and pecan shell flour (E). Binding agents are represented in the second row: sodium silicate liquid (F), polyvinyl alcohol (G), pine rosin powder (H), and dried cyanoacrylate (I). Certain materials were multipurpose and are shown in the last row: superfine rice flour (J), sugar (K), gelatin (L), wheat dextrin (M), and glycerin (N).

The results of the experiments showed that paste made of pecan shell flour, water, and sodium silicate was the best-performing material. With thorough LCA analysis, researchers concluded that ReCiPe eco-impact points were reduced by 78% (in comparison with traditional polymer-based materials) when comparing paste and ABS. ReCiPe is a method used in LCA analysis for measuring and quantification of environmental impact, which uses a point grading (eco-impact points) approach in different environmental categories, such as climate change, ozone depletion, resources consumption, toxicity, impact on ecosystems, and more. 78% reduction means that used materials, technologies, and processes were significantly improved from a sustainability aspect.

A 75% reduction in printing energy was achieved and an 82% reduction in material impact. This was a 95% reduction in impact per part compared to large commercial FFM printing of ABS. Material cost was cut in half (0.72 $/part for ABS filament, 0.36 $/part for pecan paste).

While environmental impact, cost, and energy were all reduced, the quality of the printing did not achieve the same properties as that of ABS.

Research provides us with a great example of how to achieve environmentally friendly and sustainable printing materials that could even be cheaper than polymer alternatives. There is still room for research in improving the quality of the final material, like **strength, stiffness, resolution, and surface finish**. By achieving properties similar to PLA/ABS, manufacturing and amateur industry could be motivated to shift to novel materials, specifically due to the lower cost.

Another research from 2023 (Faleschini, Trento, Masoomi, Pellegrino, & Mariano Angelo Zanini, 2023) was searching for sustainable 3D materials to replace common construction materials because the industry attributes to 37% of greenhouse gas emissions and 25% of solid waste generation. Researchers focused on earth-based materials for construction that could be modified to enable the use of 3D-printing.
The issue with typical earth-based construction materials lies in their texture which is not suitable for extrusion. The focus of the research was experimenting with different mixtures of materials, such as subsoil, sand, clay, water, lime, and natural fibers. They were looking for optimal water content, low shrinkage, and good printability.

Image 9: Earth-based materials
(source: Faleschini, Trento, Masoomi, Pellegrino, & Mariano Angelo Zanini, 2023)

In the image above (see Image 9) we can see the materials used for the experiments, which are as follows:

a) soil,
b) sand,
c) lime,
d) rice husk,
e) shredded rice husk,
f) municipal solid waste incinerator bottom ash,
g) marble dust,
h) jute fibers,
i) coconut fibers,
j) sisal fibers, and
k) goat hair.

The experiments identified the best-performing mix to be from the group of mixes that used long fibers added. The best mix was made out of:

1. sisal fibers (0.5%),
2. shredded rice husk (1.375%),
3. marble dust (1.375%),
4. lime (8.25%),
5. sand (22.78%),
6. soil (45.72%), and
7. water (20%).

Other mixes also performed well and research has shown that it is possible to produce low-priced earth-based materials with a reduced carbon footprint. Overall, the most efficient mix had a compressive strength of 1.26 MPa, embodied carbon of 0.05239 kgCO2eq/kg, and a price of 0.137€/kg.

Research emphasized that materials should also be tested in a real-world example, paying attention to the long-term performance of the material, since organic material is used in the mix.
After looking at previous research done on the topic of environmentally friendly materials in 3D-printing, we can conclude that there are alternative materials that could replace typical filament used industrially and at home. Some materials already present properties sufficient to replace filament in certain applications but not all. Additional research should be done on how to improve the printability of certain novel materials.

2.4 Environmental Impact of Cement

Cement, the main ingredient of concrete, is responsible for 5% of total human CO_2 emissions and for 7% of industrial fuel use. Half of emissions are attributed to the calcination process and the other half to energy usage during the production process. Additionally, cement production generates millions of tons of cement kiln dust, which contributes to respiratory and other health risks.

It is the world's most significant manufactured material and is also increasingly used in 3D-printing applications. The purpose of this chapter is to review the life-cycle assessment study (Huntzinger & Eatmon, 2009) on Portland cement (and alternative solutions) and to expose the controversy of using concrete solutions for environmental restoration projects.

If we look at the diagram showing the process of traditional (Portland) cement production, we can see different inputs and outputs, from emission to energy and heat in the entire life cycle as seen in the image below (see Image 10).

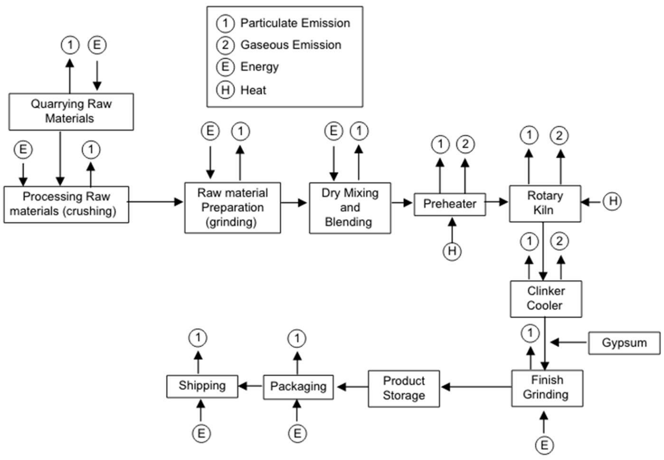

Image 10: Portland cement diagram (source: Huntzinger & Eatmon, 2009)

Cement production has multiple negative environmental impacts from different stages:

- consumption of large quantities of raw materials,
- consumption of large quantities of heat,
- consumption of large quantities of energy,
- release of large amounts of solid waste, and
- release of large amounts of gaseous emissions.

Each stage requires complex manufacturing processes, a large number and variety of materials, pyroprocessing techniques, and various fuel sources (including fossil fuels).

The study compared the life-cycle assessment results of three alternative cement applications to traditional Portland cement. The first was *blended cement* where part of clinker (a major pollutant in cement production) is mixed with other substitutes like coal fly ash, slag, and natural pozzolans. The second is traditional Portland cement but a portion of emissions are captured using sequestration in waste materials (CKD). The last is again Portland cement but CKD is recycled back into a kiln. Results, calculated in SimaPro software, are presented in the table below where each category is represented with impact points – a normalized and weighted result derived from life cycle impact assessment (LCIA) methods.
One point (1 Pt) typically represents the average annual environmental impact of one European citizen. For example, if a product scores 0.5 Pt, it causes half the environmental damage an average European creates in one year. This unit allows complex environmental data to be summarized into a single value, making it easier to compare the sustainability of different products or processes.

Table 3: LCA of Portland and alternative types of cement (source: Huntzinger & Eatmon, 2009)

Environmental impact category	Traditional	Blended	Recycled CKD	CO_2 Sequestration
Greenhouse	0.088	0.069	0.088	0.084
Acidification	0.043	0.034	0.043	0.043
Eutrophication	0.006	0.005	0.006	0.006
Heavy metals	0.204	0.161	0.204	0.204
Carcinogens	0.003	0.003	0.002	0.003
Winter smog	0.039	0.031	0.039	0.039
Summer smog	0.009	0.007	0.009	0.009
Energy resources	0.050	0.040	0.050	0.050

Because the pyroprocessing step is the most energy-intensive, blended cement has a lower impact on global warming overall. Blending alternative materials to reduce the amount of clinker additionally lowers other environmental impacts.
CO_2 sequestration method has a slightly lower impact score while recycled CKD made little to no difference in the impact score.

Cement, a major ingredient of concrete and mortar, has a negative impact on the environment. As will be explored in the following chapters, concrete is a common material used in 3D-printed restoration solutions, and after examination of its life-cycle assessment above, we can conclude that alternative environmentally friendly concrete solutions should be explored to ensure truly sustainable solutions.

Another explored alternative is concrete recycling. While concrete from demolition is actively used as rubble (often in road construction), another possibility is the use of recycled concrete aggregate (RAC) instead of natural aggregate which supports a circular economy and reduces the need for non-renewable natural material extraction. However, studies have shown that cement production has the largest negative environmental impact, followed by transport, and aggregate production is actually the lowest contributor. However, when comparing RAC to natural aggregate, research shows that the impact of cement and aggregate production life-cycle phases for RAC is slightly higher (energy use, global warming, eutrophication, and acidification). This is largely contributed to the larger transport distance for RAC and also different modes of transport. (Marinković, Radonjanin, Malešev & Ignjatović, 2010)

As transportation is the largest contributor to the environmental impact difference between RAC and natural aggregates, optimizing RAC transportation can make it more sustainable than natural aggregates while remaining beneficial in replacing the use of non-renewable natural materials. (Zhang et al., 2019)

It is important to note, that some research also argues that RAC has some additional environmental benefits in comparison to natural aggregate as it can be used as a carbon sink and can significantly reduce CO_2 uptake during secondary life. (Marinković, Josa, Braymand, & Tošić, 2023)

2.5 Environmental Impact of Clay

Another material gaining traction in the additive manufacturing industry is clay. While the environmental impact of clay depends on various factors, such as the origin of raw material and the production process, it is important to do a rough overview of production and its environmental effects.

Mukherjee (2013) argues that the major source of air emissions in the fired clay building products industry comes from vehicular traffic, clay extraction, transport, and grinding while kiln and drying processes have minimal emissions.
The main issues from clay quarries are due to the nature of mining operations which are mostly done in the summer months when dust generation has maximum potential. However, many of these issues can be mitigated using the following approaches:

- covering transport trucks,
- watering stockpiles,
- mining when wind conditions are calm,
- material from the conveyor belt should fall less than 1 meter, and
- storage should act as a windshield.

Another issue is stormwater which is contaminated at mines, roadways, plants, and equipment by fuels and lubricants. However, process wastewater is generally minimal, except for adding metal oxide for the pigmentation of roof tiles.
To mitigate the issues stated above, stormwater should be directed away from the clay product industry sites. At sites, the floor should be sealed and contaminated stormwater should be contained and filtered using sediment ponds.

Most of the greenhouse gas emissions in the clay brick industry come from fossil fuel sources that are used in the clay brick-making processes. However, these have been successfully replaced by renewable energy sources.
Generally, clay masonry is accepted as a sustainable product. Most of the energy consumption comes from the quarrying of raw materials as stated above but also from the firing of clay. If brick is fired by renewable energy sources, it is accepted as the least energy-consuming building product in the market today.
Additionally, studies have shown that waste generation is 1.2 g per kg of product. Clay products can also be recycled and generally have a very long service life.

A study from 2017 (Marcelino-Sadaba, Kinuthia, Oti & Meneses, 2017) performed an extensive LCA analysis of clay products and compared them with concrete in building applications. Based on experiment data of raw compressive strength, it concluded that clay-based materials are much more suitable for sustainable construction and also achieve a higher per-unit strength.

The study also pointed out that while unfired clay systems have a lower performance than their fired counterpart, they are more sustainable due to the lower energy consumption. However, more research should be done on their applicability.

The key takeaway of evaluating clay as a sustainable material is that clay-based systems pose less of an environmental threat than concrete. However, sustainability varies widely and is dependent on multiple factors, such as proper mining and processing infrastructure, sustainable energy resources in firing and transport, and recycling.

3 Marine Ecosystems Restoration

The world's coastal ecosystems are incredibly diverse. They include mangrove forests, coral reefs, vegetation beds, dunes, deltas, and more. They are also very complex, shaped by abiotic and biotic forces, such as tides, waves, currents, light penetration, decay of plants, and, of course, man-made features.

Image 11: Mangroves
(source: Tanja Tajnik)

These ecosystems also have immense ecological, economic, and social importance. Their distinct structure, diversity, and flow of energy provide essential homes for numerous aquatic plants and animals. They contain goods, such as food (for humans and animals), salt, minerals, oil resources, construction materials, and more. It was estimated that by 2002, 41% of the population lived at or near the coast. The majority of countries have 80-100% of the population living within 100 kilometers of their coast. 18% of all lands within 100 kilometers are altered – either for urban or agricultural use. (Martínez et al., 2007)

Unfortunately, these important areas are being increasingly degraded by both natural and anthropological causes. Natural causes might include tropical cyclones, climate fluctuations, and flooding whereas anthropological causes include exploitation for development, recreation, industry, over-population, and over-fishing. Due to the known importance of coastal areas, researchers have achieved the planning and execution of many restoration projects and monitoring activities of restoration. (Reid Nichols, Zinnert, & Young, 2018)

While the loss of marine habitats and ecosystems can be counteracted by removing certain anthropological threats, restoration, and rehabilitation are still essential and crucial to areas where ecosystems cannot recover due to the physical modifications to the coast. **Ecosystem restoration** is a process that assists the recovery of an ecosystem that has been degraded, damaged, or destroyed, and **ecosystem rehabilitation** means the replacement of structural or functional properties of the damaged or lost ecosystem. (Bayraktarov et al., 2016)

However, these projects face a big issue – the cost. The efforts require a combination of public and private initiatives for success, which is very costly.
Research (Bayraktarov et al., 2016) built a database of such projects from the last 40 years and investigated their costs, which varied considerably between ecosystems (coral reefs, seagrass, mangroves, saltmarshes, and oyster fields).
The median restoration cost for all ecosystems was 80,000 $/ha while the average cost was 160,000 $/ha. Total project cost (capital and operational) was between 150,000-400,000 $/ha.

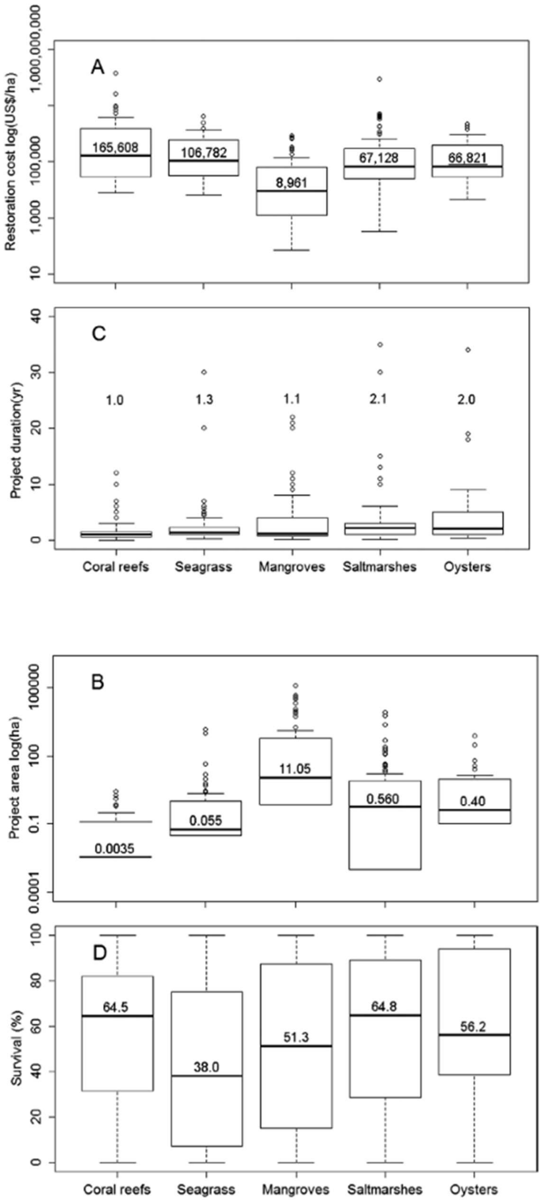

Image 12: Cost, survival, and project duration (source: Bayraktarov et al., 2016)

Pripombe dodal [MŽ2]: Premakniti na prejšnjo stran

Researchers concluded that the cost depends on:
1. ecosystem restored,
2. economy of the country, and
3. restoration technique.

Interestingly, the cost of marine coastal restoration projects was observed to be 10-400 times higher than the restoration cost of inland wetlands, freshwater systems, temperate forests, and grasslands.
Restoration success had no correlation with the cost of the project but varied between different ecosystems and techniques applied. Coral reefs and salt marshes had the highest survival rates while seagrass had a much lower rate.

The most important conclusion of the research was that coastal ecosystem restoration projects are feasible but research is still in an early phase. There is room for improvement in long-term monitoring and observations but also in the techniques applied to different ecosystems. 3D-printing technologies could perhaps pose a solution to the high costs of these projects.

3.1 Coral Reef Restoration

For the past decades, the global coral reef coverage has decreased by 19%. It is estimated that more than 60% of coral reefs are under immediate threat from overfishing, destructive fishing, coastal development, and pollution. All of the stated is in addition to climate change. (Bayraktarov et al., 2016)

In the above literature of past studies, it was concluded that coral reef restoration projects are feasible, even showing the highest survival rate among other observed restoration projects. For the thesis, an in-depth understanding of reef restoration techniques is essential.

Until recently, most of the marine conservation projects focused on passive restoration, rather than active. However, recent research has shown that optimal conservation outcomes require both habitat protection and active restoration efforts.
The field of coral restoration is dominated by coral transplantation techniques, using fast-growing coral species. A study from 2020 (Boström-Einarsson et al., 2020) observed 362 case studies of mentioned projects.

<u>Species used</u>

The top five coral species used in observed restoration projects were *Acropora cervicornis, Pocillopora damicornis, Stylophora pistillata, Acropora palmata, and Porites cylindrica.* Average survival rate was 66% while some species survival rate exceeded 90%. The most commonly used species were from the genus *Acropora,* likely due to their endangered status.

<u>Restoration methods</u>

Out of observed studies, 20% used the method of **direct transplantation** which includes immediate transplantation of coral from a donor reef to the recipient. However, this method is not considered sustainable because it has negative effects on donor corals.
A more sustainable method is **coral gardening** where smaller fragments are first introduced to either field-based or land-based nurseries. Nurseries protect the corals in their most vulnerable stage, growing them until they are either ready to be transplanted or again fragmented for multiplication. This method was observed in 48% of mentioned studies.

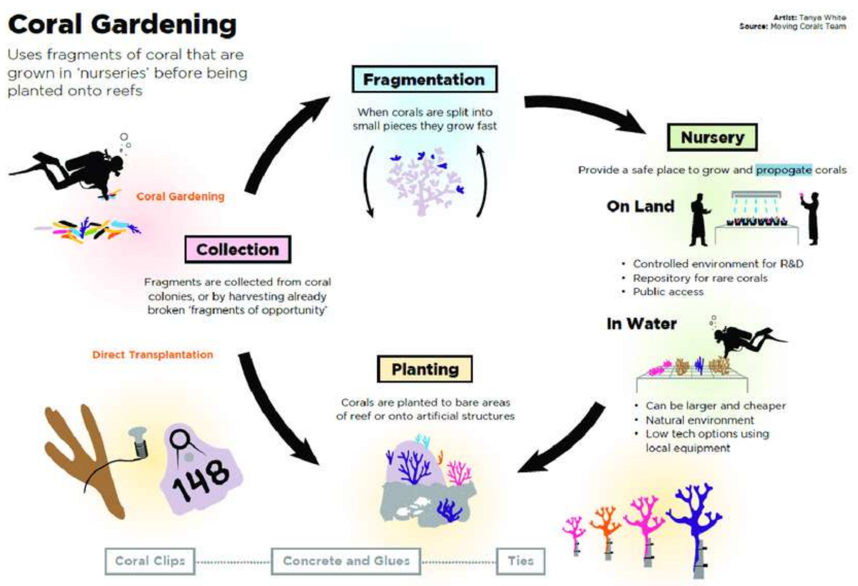

Image 13: Coral gardening and direct transplantation
(source: https://www.researchgate.net/figure/The-coral-gardening-process_fig5_349126321)

21% of observed studies also included the creation or addition of substratum which has an important role in the survival rate of transplanted corals. Most commonly, these projects include **artificial reefs** that resemble a natural substratum and best properties for coral's survival rate. Other techniques used are natural **substratum stabilization** and **substratum enhancement.**

Issues observed

Research (Boström-Einarsson et al., 2020) has pointed out a serious issue about research being done on restoration projects. 60% of all projects had less than 18 months of monitoring the restored sites. Most projects were also relatively small in spatial scale because the median size was 100 square meters.
By definition, a restored ecosystem *contains sufficient biotic and abiotic resources to continue its development without further assistance or subsidy.*

3.2 Artificial Reefs

Artificial reefs are defined as man-made structures, intentionally placed either on sea-floor or submerged to enhance marine habitats and ecosystems. They mimic natural reefs and provide shelter, food, and breeding grounds for various marine organisms. They are most commonly constructed using materials like concrete, steel, sunken ships, and other objects. (MarineBio, 2024).

Apart from previously stated coral reef restoration, artificial reefs have other important goals:

1. biodiversity enhancement,
2. fisheries management,
3. erosion control,

4. diving and recreational opportunities, and
5. coastal protection.

3.2.1 Structure Complexity and Substrate Material

Research from 2013 (Graham & Nash, 2013) analyzed 158 studies between 1972 and 2010 on the topic of structural complexity in coral reef ecosystems. It was concluded that there is a positive correlation between structural complexity and coral cover, branching coral cover, fish density, and biomass cover. However, there was a negative correlation between urchin and algae coverage.
As a result, the importance of structural complexity as a variable in successful coral reef restoration was proven. Research suggests that maintaining and enhancing complexity in existing and new reefs should be an integral part of monitoring and research.

As stated above, many studies emphasize the importance of structure parameters in artificial reefs on the success of restoration projects. Berman, Levy, Parnas, Levy, and Tarazi (2023) argue that structure complexity is important in artificial reefs because it allows the **accumulation of benthic communities,** which supply corals with essential nutrients and microbes. However, complexity is not the only property of artificial substratum that is important. Researchers (Reyes & Yap, 2001) observed the effects of substrate material choice on the settlement and community development. They performed an experiment where they used three different materials as substratum choices – concrete, rubber, and crushed coral rubble. Materials were formed into 10 cm x 10 cm blocks and placed in two locations: one was 0.25 m away from a live coral reef, and the other was bare sand (5 m from live coral).
The results of coral larvae recruit on plates varied significantly between locations and substrate materials. Most recruits were found on the coral plate, closely followed by the concrete. Rubber had the least recruits, with a large margin between the first two substrates. Results also show that proximity to live coral reefs has a big impact on the mean number of recruits on artificial substrate (see Image 14).

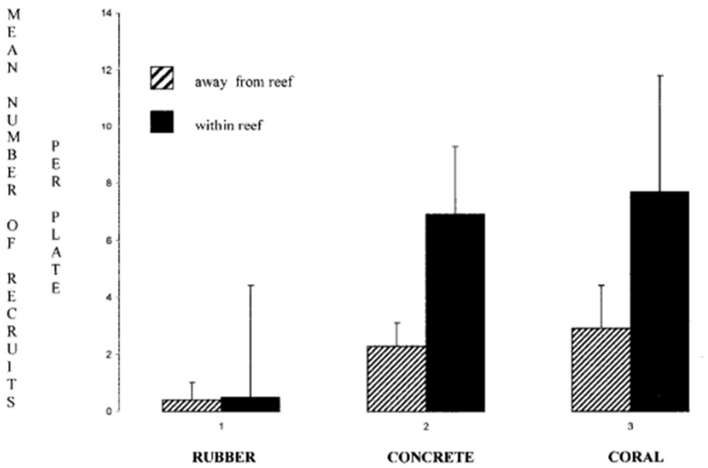

Image 14: Number of recruits on different substrates (source: Reyes & Yap, 2001)

Research determined that the biggest factor for larvae attachment was the roughness of the material, suggesting that crushing corals to different settings could produce even better results. It also concludes that as many restoration projects involved submerged rubber tires, they are not only an environmental hazard but also a bad-performing substrate for artificial coral reefs.

3.2.2 3D-Printed Artificial Reefs

While artificial reefs come in many forms, researchers (Carr & Hixon, 1997) agree that structure complexity plays a pivotal role in success of the restoration projects. Research from 2001 (Sherman, Gilliam, & Spieler, 2002) concluded that artificial reefs with more structural complexity and less void space had greater fish abundance, species richness, and biomass than those with less complexity and more void space.
One of the benefits of 3D-printing is its ability to produce complex structures where manufacturing costs are much lower than in traditional methods which is why 3D-printed artificial reefs are becoming increasingly interesting for researchers working on coastal restoration projects.

In Chapter 3.1, we investigated coral restoration methods where coral gardening currently dominates the field. Researchers (Berman, Levy, Parnas, Levy, & Tarazi, 2023) observed that most coral nurseries today attach coral fragments to:

- epoxy glue (30%),
- cable ties (18%),
- cement (10%),
- cyanoacrylate glue (4%),
- wire (3%), and
- ropes (3%).

All of the current approaches are disposable, prone to deterioration, and impact coral health, which affects population management, scalability, and feasibility of restoration projects. Artificial reefs (and artificial substrates) mitigate these issues which is why they are the more appropriate approach to coral restoration.
In Chapter 3.2.1 we discovered the importance of structure complexity and substrate material for coral growth and health. Similarly, the observed research concludes with identical outcomes. As a result, they argue that 3D-printing has allowed researchers to implement a better approach to digital fabrication and parametric design, without the need for molds and difficult production techniques.

3D-printing, combined with 3D scanning technology, is becoming increasingly popular by scientists today. One of many examples of the combination of these two technologies is research from 2021 (Albalawi et al., 2021) where scientists explored the fabrication of artificial natural-based coral skeletons for expediting the growth rate of live coral samples while minimizing the costs.
They approached the issue by first scanning a live coral sample, creating a 3D model, and then reproducing it with a printer. There were two approaches to printing methods – method A and method B. Method A involved printing a PLA model first and then creating a mold for calcium carbonate photoinitiated ink (CCP) while method B involved direct 3D-printing with CCP.

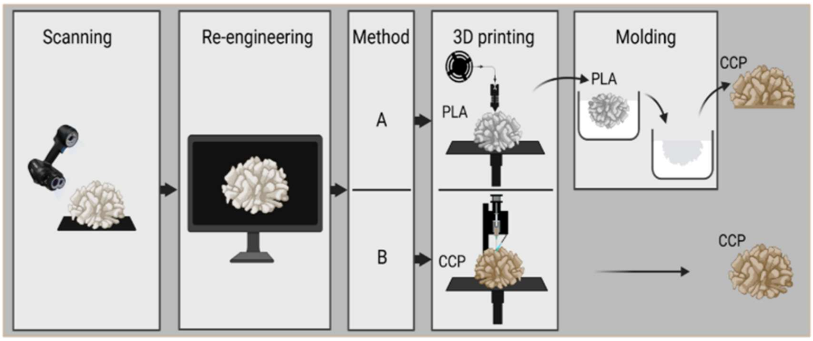

Image 15: 3D-printing coral skeletons
(source: Albalawi et al., 2021)

Berman and others (2023) also emphasized morphological complexity and diversity for the success of restoration projects. They used a parametric design tool to create 87 complex shapes which were 3D-printed with clay and placed in the northern tip of the Red Sea, placed in the coral reef environment. After two years, they observed abundant marine organisms settling and recruiting, concluding that ceramic printing of high morphological complexity is viable for restoring coral reefs.

Extensive research from 2021 (Matus et al., 2021) printed 3D-modeled tiles from soil erosion samples with PLA (see Image 16).
The purpose of the experiment was to prove the influence of surface morphology and chemical composition on the growth and propagation of transplanted corals.

The PLA model of tiles was then used for silicone mold manufacturing, which was followed by producing the final tiles with five different cement mixtures and one commercial tile. Due to space limitations of the test aquarium, only 4 of the tiles were used (including a smooth surface control tile).

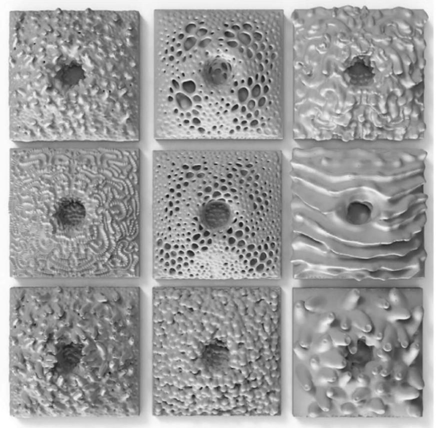

Image 16: Soil erosion texture tiles
(source: Matus et al., 201)

In the cavity in the center, Montipora Confusa,
Montipora Undata, and Montipora Danae were placed and monitored weekly. Crustose Coraline Algae (CCA) evolution and selected coral growth were observed. From the third week of monitoring, CCA began to cover the substrate tiles, especially the three textured tiles on material composed of Creme Fatima Limestone under 70 μm, with added CEM II B-L and added quartz. Other groups also showed growth of CCA but in lower amounts. CCA covered much less of the area on the smooth control tile.
After weeks of observation, the tile with the most structural complexity had the largest coverage of CCA and the highest subsequent coral growth, providing another proof of the importance of substrate complexity. Tile composited from limestone under 70 μm, with added CEM II B-L and added quartz was observed to have the most extensive coral growth of Montipora Danae.

To validate the impact of chemical composition, another experiment was done with three groups of different materials: one with limestone cement, one with cement and quartz, and one with commercial coral tile. Again, CCA and coral growth were much higher on the tile with limestone presence than in the other two groups.

Observed experiments validate the important role 3D-printed artificial reefs can have in coral restoration projects, while also providing valuable insights on the previously observed importance of structure complexity and chemical composition of substrate.

4 Urban Ecosystems Restoration

Urban green space is incredibly relevant to wildlife conservation, human welfare, and climate change adaptation. For billions of people, urban ecosystems are the only daily contact with nature, which has proven to be very important for their well-being and also education. (Klaus & Kiehl, 2021)

In the past decades, there was a huge shift towards living in the cities where more than half of the world's population lives today. Ecologists have focused their efforts on addressing the negative effects of urbanization on the environment and started projects to restore remnants of natural diversity.
While many such projects were executed successfully, researchers have started to realize that the evaluation metrics for these restoration sites cannot be achieved in all cases. Some of the criteria, like the presence of indigenous species and comparable diversity to »reference« sites, cannot be achieved in urban areas.
Gobster (2010) argues that the *urban* in urban ecology places people's values, perceptions, and actions directly alongside ecological aspects in landscape change. He emphasizes that such projects have both social and ecological constraints on particular sites.

Another research from 2012 (Standish, Hobbs, & Miller, 2012) also mentions the important role of the human dimension in urban ecosystem restoration because that is where humans and nature co-exist. Researchers state four options for urban restoration:

1. conserve and restore nature at the urban fringes,
2. restore remnant patches of urban nature,
3. novel ecosystems: manage or transform into green space, and
4. gardening.

They also state the importance of ecologists working together with urban planners, developers, architects, and other stakeholders to address the issue of space availability for urban nature which requires a lot of ingenuity.

While there are numerous topics on how to transform and restore urban ecosystems, the following chapters will focus on novel technologies and approaches, specifically those similar to green urban structures (green walls and green roofs), because these could be highly influenced by the rapid adoption of 3D-printing technologies.

4.1 Green Urban Structures

In times of rising urban densification, researchers emphasize its effects on global climate change, urban heat island effect, urban noise, air pollution, and water management. One of the proposed ways to deal with these issues is green urban structures which come in many forms. The most common types are green roofs and green walls which have important environmental, social, and economic benefits that improve buildings' performance and the surrounding urban environment. (Manso, Teotónio, Silva & Oliveira Cruz, 2021)

Green roofs are multi-layered systems that enable the greening of a building's horizontal structures by the growth of different types of vegetation. Multiple layers are needed for the support, protection, and improvement of system performance. Normally, they are structured in the following order:

1. vegetation layer,
2. growing medium (substrate),
3. filter layer,
4. drainage layer,
5. insulation layer (optional),
6. root barrier, and
7. waterproofed roof structure.

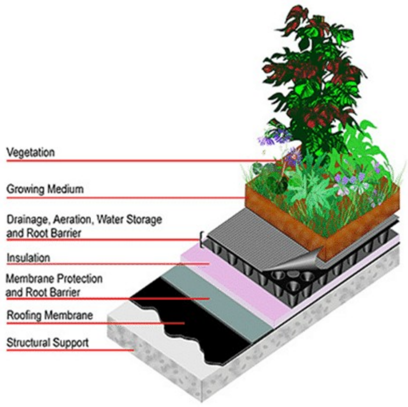

Image 17: Green roof layers (source: Manso, Teotónio, Silva & Oliveira Cruz, 2021)

The minimal slope needed for green roofs is 2% to enable drainage of excess rainwater not retained by the primary layers.
While they are becoming increasingly popular, they are, however, more expensive than traditional roofs because they demand the use of more expertise, additional material, higher weight load capacity, and maintenance.

Depending on the depth of the substrate and plants used, green roofs can be classified as intensive, semi-intensive, and extensive. Intensive roofs use thicker substrates and larger plants but also require frequent irrigation and maintenance. Extensive roofs are more common because they require a thinner substrate layer and do not require as much maintenance. Succulents, mosses, grass, and wildflowers are commonly used for extensive systems due to their short root structure and compatibility with limited water supply. (Manso, Teotónio, Silva & Oliveira Cruz, 2021)

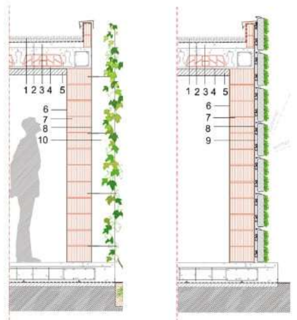

Image 18: Green facade and living wall (source: Manso, Teotónio, Silva & Oliveira Cruz, 2021)

Green walls are all systems that enable the greening of vertical building structures and are divided into two categories – green facades and living walls. Green facades are normally systems that use climbing plants that grow against the existing structure or might have indirect support (wire, mesh, etc.) while living walls are modular or continuous systems that are mounted on the existing structure and allow a uniform vegetation growth of a variety of plant species. The latter usually also require irrigation and nutrient supply. (Manso, Teotónio, Silva & Oliveira Cruz, 2021)

Manso, Teotónio, Silva, and Oliveira Cruz (2021) performed an extensive literature review of 129 research articles examining the urban and building benefits, as well as costs, of green walls and green roofs.

4.1.1 Building Scale Benefits

Multiple reviewed studies have demonstrated that green walls and green roofs **reduce energy consumption**. When comparing intensive green roofs with black roofs (especially non-insulated ones), they reached 84% energy savings in the cooling period and 48% in the heating season. Intensive green roofs also improved energy efficiency in the heating period compared to white roofs but not in the cooling period. Energy savings largely contributed to

the additional layer of insulation on such roofs which is why they were more favorable in the colder climates.
Green walls were examined in the hot-summer Mediterranean climate where it was demonstrated that in the cooling period, the green facade can contribute up to 34% energy efficiency and living walls up to 66%. This largely contributed to the additional insulation layer, as well as shadowing and surface temperature reduction.

Due to lower solar radiation absorption and heat transformation of green roofs, multiple observed studies also demonstrated a **higher photovoltaics performance** when modules were placed above such systems because photovoltaics system performance is higher when cells are exposed to cooler ambient temperatures. The average minimum increase in photovoltaic performance was 1.59% and the average maximum increase was 3.35%.

Some of the observed studies demonstrated the positive impact of green roofs on **sound transmission reduction**. While the effectiveness of the decrease in noise levels varies significantly depending on the composition of different layers, water content, and also plant species, the demonstrated decrease was between 5 dB and 20 dB, depending on the frequency. One study has also observed a noise reduction of 2 dB when using a living wall and 3 dB when using a green facade.

Green roofs and walls also have a huge potential to be used in **greywater treatment** because substrate and plants can function as biofilters with the use of oxidation, filtration, sedimentation, adsorption, microbial assimilation, and activity. Studies achieved conclusions that green walls can remove 80–90% of total suspended solids, over 90% of biological oxygen demand, 30–50% of total nitrogen, 15–30% of total phosphorus, 30–70% of chemical oxygen demand and 20–80% of E. coli.

Multiple layers placed on top of the waterproof membrane act as a protective barrier from solar ultraviolet radiation, contributing to the **longer in-service life** of green roofs compared to traditional roofs. Described life duration of such roofs is estimated to be 50 years or more while 90-year-old roofs exist in Berlin that still have all the original layers. While these roofs are more expensive, the longer service life could be a reason to opt for such a solution, additionally to all the other benefits.
On the other hand, green walls are not as durable. While their in-service life is expected to be 50 years, other maintenance needs come into play. 5-10% of plant species need to be replaced every year while irrigation piping may need a replacement every 7.5 years due to salt crystallization.

4.1.2 Urban Scale Benefits

Urban areas are affected by the urban heat island effect, which is influenced by surface temperature, air pollution, wind speed, and limited green spaces, and has a negative effect on public comfort and health, and also causes an increase in energy consumption for cooling. The previously mentioned ability of plants to absorb solar radiation, as well as their cooling effect through evapotranspiration, can contribute to the **urban heat island effect mitigation**. The minimum and maximum average reduction of surrounding temperature in observed studies of green roofs was 1 °C and 2.3 °C, and the average urban temperature decrease in green walls was 1.37 °C.

Urban areas are built with materials that lack **water retention capacity** and it is very common to see sewage systems overflow when intense rainfall occurs. Green roof multi-layer architecture can retain water, especially intensive green roof systems where the minimum average stormwater runoff reduction observed was 33% and the maximum average was 90%. Additionally, such systems also contribute to higher **runoff water quality**.

Air pollution is a common issue in cities, contributing to negative health effects on humans who are often exposed to levels above the limit values. Plants offer a solution to the issue with their ability to **sequester air pollutants and consume carbon dioxide**. In the observed studies, both green roofs and green walls contributed to a higher average removal capacity of O_3, NO_2, PM_{10}, SO_2 and CO. However, certain studies observed an average increase in certain particles, which might be caused by certain green roof system characteristics, low windspeed, and lack of horizontal airflow, concluding that the effects of such systems on air quality are not straightforward and require further research.

There are also other non-quantifiable benefits to green roofs and green walls. One of the examples is their ability to promote citizens' health and well-being because green spaces contribute to mental and physical health, providing psychological relaxation and stress alleviation.

4.2 Bioreceptivity

Olivier Guillitte first defined the term bioreceptivity in 1995 as a concept for building ecology studies: *the ability of a material to be colonized by one or several groups of living organisms without necessarily undergoing any biodeterioration*. He aimed to distinguish the term from *biodeterioration* and *biodegradation* which both have negative connotations. (Sanmartín, Miller, Prieto, & Viles, 2021)
According to Guillitte, there are four types of bioreceptivity:
1. primary,
2. secondary,
3. tertiary, and
4. quarternary.

Primary bioreceptivity is a material's ability for colonization by primary colonizers when material properties have not been substantially modified by either biotic or abiotic factors. Usually, the first colonizers are algae and cyanobacteria because they require only inorganic material to survive and serve as a primary layer for further colonization by other species. Secondary occurs when material properties evolve through weathering by environmental and/or colonizer factors. Tertiary occurs when human-induced factors are included, such as cleaning or restoring the material. Quarternary is quite similar to tertiary, but the human-induced factors included are either chemicals or coatings that leave residue on the material.

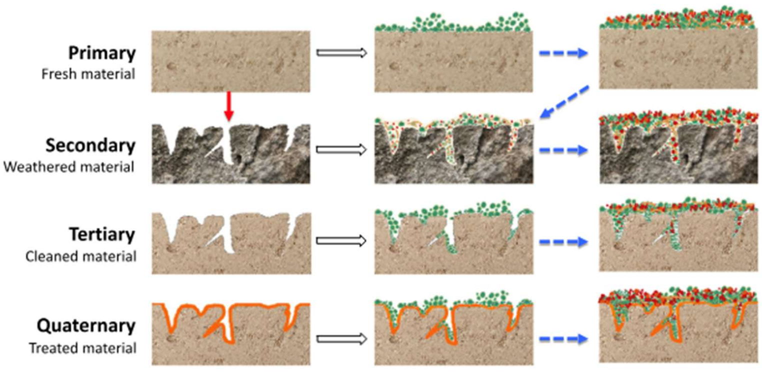

Image 19: Bioreceptivity types
(source: P. Sanmartín, Miller, Prieto, & Viles, 2021)

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Researchers around the world have been shifting their focus to the bioreceptivity of concrete in urban settings because the material's properties like porosity and water absorption support the growth of biofilm, algae, and moss.
One of many articles that reviewed novel approaches to greening urban areas through the bioreceptivity of concrete was published in 2023 by Delft University of Technology (Veeger, Nabbe, Jonkers & Ottele, 2023) where researchers focused specifically on mosses. Moss has a big potential to add more green to cities and even provide related benefits. It is extremely tolerant to desiccation, has many ways of reproduction (spores, propagules, and fragmentation), and ability to gain nutrients from air and water through stems and leaves. While it does naturally colonize concrete in urban settings already, researchers also focused on new bioreceptive concrete emerging in the last decades.

While they emphasize that the primary bioreceptivity of concrete in urban settings is low, through weathering and human intervention, concrete already supports secondary, tertiary, and quarternary bioreceptivity. However, there is a shift happening lately that rather than mitigating biological growth on materials we could support creating new materials that have high primary bioreceptivity.
This can be achieved by higher water retention properties, which can be achieved by increasing the aggregate's porosity, water-to-binder ratio, or even both. Crushed expanded clay and vermiculite as aggregates have been proven to increase the bioreceptivity of concrete.

A common approach has also been changing the surface texture, specifically roughness, which increases water retention properties. Additionally, higher roughness provides organisms with a protected microhabitat, improving their establishment and survival.

The last observed factor that increases bioreceptivity is changing the chemical composition of concrete. Traditional concrete, made based on Ordinary Portland Cement, has a very high pH, which is not favorable to microorganism growth. Multiple studies have shown promising results in lime types of cement and magnesium phosphate cement. However, there have so far been **no studies that focused specifically on the effects of pH on bioreceptivity, and should be explored in the future.**

4.2.1 Benefits

While quantifying the benefits of moss and algae on concrete in an urban setting is difficult, specifically given the lack of research, researchers from Delft University of Technology (Veeger, Nabbe, Jonkers & Ottele, 2023) have made inferences based on ecosystem services provided by other plants.

They have come to some of the conclusions as observed in the thesis in chapters 4.1.1 and 4.1.2, which was expected as they have inferred the benefits of green building structures. The four quantifiable benefits mentioned are:
1. improved air quality,
2. urban heat island mitigation,
3. urban noise attenuation, and
4. stormwater retention.

However, there are important differences between these benefits because in chapters 4.1.1 and 4.1.2 some of the benefits were provided by the substrate layer and bioreceptive concrete lacks this layer. However, mosses have great insulating and water retention properties, which mitigates the need for substrate layers on such structures.

4.2.2 3D-Printing Potential

3D-printing, as observed in previous chapters, is a suitable tool for creating complex and custom shapes that need to be tailored to each use case. Bioreceptivity can be increased by tuning structure parameters of material roughness, porosity, and micro-groove formation, which by proper filament choice and model design can be optimized using 3D-printing technology.

Experimental research from 2023 (Cheng & Lharchi, 2023) focused on parameters to increase the bioreceptivity of custom 3D-printed structures. After researching previous studies, the importance of factors, such as geometry, surface finish, and ability to retain water was defined. Additionally, researchers focused on ensuring capillary water flow across the structure by creating models that direct the fluid flow path.

An experiment was conducted by creating clay prototypes with various parameters to observe their impact on water diffusion, filtration, channeling, and bio-growth. The primary focus was the creation of channels and cavities to control water movement, which differed in channel radius, depth, and merging threshold.

Experiments were split into 4 categories. Experiments 1 and 2 tested the impact of layer height, nozzle thickness, and curvature on water diffusion (movement of water through clay). Experiment 3 observed the relationship between printing parameters and bio-growth. Experiment 4 focused on the water channeling effects.

Image 20: Experiment 3 (source: Cheng & Lharchi, 2023)

Results of the experiments have shown that larger nozzle width and layer height produced a more porous final product, which contributes to 3D-printing as a suitable method for creating bioreceptive materials simply by choosing the right nozzle.

Curvature affected both diffusion and moss growth. Diffusion was better when sharper loops were present on the test cups. However, moss growth was highest in the tiles where loops and inner-to-outer loop ratio were smaller. However, this could be attributed to the surface visibility.
The results of the last experiment were not straightforward and, therefore, no conclusions were gathered on the topic of water channeling effects.

Even though not all results provided a clear conclusion, researchers paved the path to future modeling of bioreceptive structures. Porosity can be increased with proper nozzle width and layer height, providing great diffusion and adherence properties.

Another research from 2023 (Abdallah & Estévez, 2023) explored the concept of bioreceptivity in an urban setting by creating two experimental tiles with different patterns and observing algae growth. Patterns were modeled using the reaction-diffusion Gierer-Meinhardt model. Pattern 1 was a polar periodic pattern with regular 3 mm spacing while Pattern 2 followed a labyrinth strip path of 500 μm spaces and wells. Patterned tiles were printed using PLA.

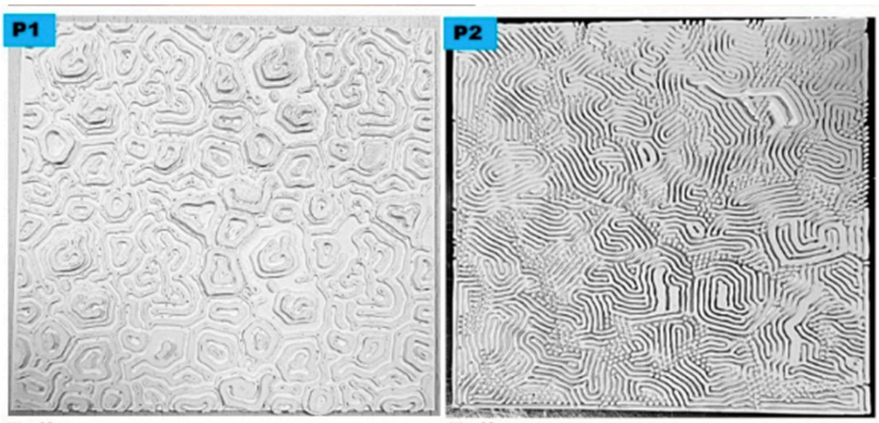

Image 21: Patterned tiles
(source: Abdallah & Estévez, 2023)

Various algal strain growth was observed during the experiment where *Pyrocystis fusiformis* had the highest growth yield, followed by *Oedogonium foveolatum* and *Mougeotia*. After 4 weeks, the density of *Pyrocystis fusiformis* on Pattern 1 increased 1.3 times while on Pattern 2 it increased 1.53 times. On Pattern 2 *Microspora* density increased the most – 1.65 times. All strains observed had higher density observed in Pattern 2, concluding that its bioreceptivity is superior to that of Pattern 1.

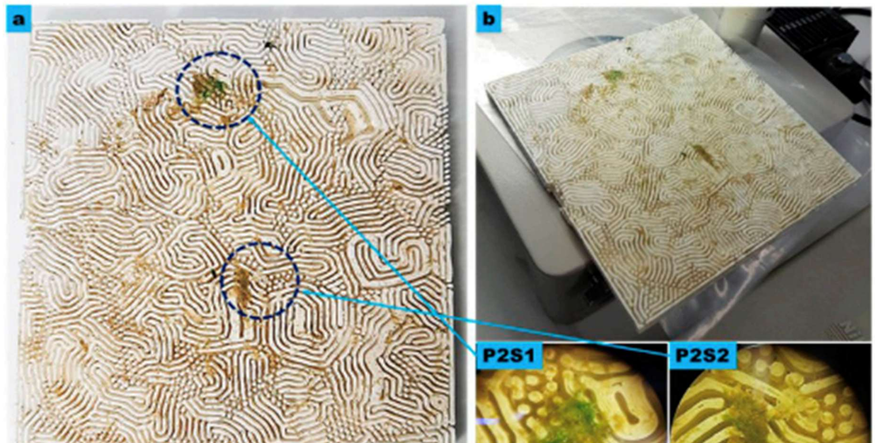

Image 22: Pattern 2 algae density
(source: Abdallah & Estévez, 2023)

Conclusions from both observed pieces of research contribute to the utilization potential of 3D-printing (and modeling) for creating complex structures from various materials, with the ability to control surface porosity. Utilizing the correct modeling approach, materials can be optimized to allow for higher bioreceptive features, enabling researchers to produce urban solutions that increase biodiversity and could provide significant urban and building benefits.

5 Case Study: Coastruction

Coastruction is an environmental startup from the Netherlands aimed at marine ecosystem restoration. Its primary goal is coral reef restoration and its secondary goal is coastal protection. The company was chosen for a case study because it utilizes 3D-printing and modeling technology for restoration, as well as a scientific approach to the assessment of sustainable materials and production processes.

5.1 Materials and Technology

Coastruction utilizes an innovative approach to 3D-printing artificial reefs, which makes them stand out in comparison to most of the other restoration projects. They developed an in-house custom powder bed 3D printer (binder jetting technology), which allows them to offer users to print with a variety of local environmentally friendly materials.

Structures can be printed using a wide choice of types of cement combined with natural materials, such as crushed shells, coral rubble, and local sand. They exclusively use water, no chemicals or additives as binding agents which are added layer-by-layer to powdered mix. An example of an added binder to a powdered layer is seen in the image on the right (see Image 23).

Image 23: Layer with added binder (source: Coastruction)

Their technological approach has various advantages:

1. Freedom of material was already mentioned, which is incredibly important as it allows the choice of appropriate substrate bed per given location. This can prevent the use of unsuitable, non-native, and environmentally hazardous materials to the environment.

2. Sustainable process, which is made possible by the use of powder bed 3D-printing. Without the need for a heated nozzle, energy consumption, and particle emissions are much lower than in traditional additive manufacturing. Excess material can be used for further production directly, minimizing waste and carbon footprint, which is additionally lowered by the use of an optimized cement-filler ratio. They enable printing on location, which in turn reduces transport-related emissions and waste, such as fossil fuel and packaging material.

3. Freedom of shape, the main benefit of 3D-printing, allows the production of complex, biomimetic shapes, which is an important factor consistently emphasized in coral reef restoration projects and studies (see Chapter 3.2.1).

4. On-site production reduces transport-related emissions and waste, such as fossil fuel and packaging material. They use local staff and resources which allows for successful site-specific design.

5.1.1 Printers

The company is currently offering two printers – *Idefix* and *Asterix*. First is a small-scale desktop unit with a print base of 25 cm x 25 cm x 15 cm. Its target use case is testing new

materials and producing experimental models (either testing shapes or different substrates). It offers 2.5 mm and 5 mm resolution.
Asterix on the other hand is a heavy-duty printer with a base of 1 m x 1 m x 1 m, with the ability to work under difficult conditions, such as dust, heat, and salt water. It has a resolution of 2.5 to 5 mm, which is customizable.

Image 24: Idefix (left) and Asterix (right)
(source: Coastruction)

Coastruction envisions a third printer in the future, called *Obelix*, which will be a large-scale mobile printer, able to work stand-alone on the project's location – off the grid. It will be a system inside a modified shipping container, which can be shipped to any location around the world. It will have the ability to print up to 6 m^3 and much higher production speed compared to *Asterix*. Printing could even take place during shipping.

The company's focus is set on creating a network of *Obelix*-style printers, which will work off-grid in a continuous fashion. The cleaning machine will support the production line and also cure the printed structures.

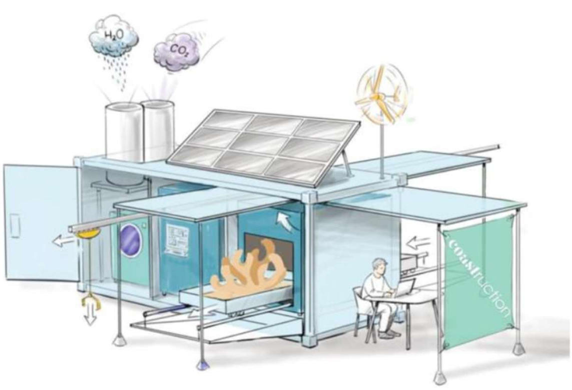

Image 25: Obelix vision
(source: Coastruction)

Coastruction has been testing its approaches for years, developing the perfect approach to printing said structures, and through the experience they have identified certain requirements that must be followed:

- The minimum distance between printed parts must be at least 10 mm.
- The minimum diameter of holes must be 10 mm.
- A 6 mm gap must be present between a printed part and the edge of the printing area.
- Models can be stacked but require a gap of 20 mm.
- The aspect ratio of 1:4 is recommended for protrusions connected on only one end, and 1:5 for those connected on both ends.

5.1.2 Materials

The main material used in coastruction is cement and their documents imply that they are familiar with the negative environmental impacts of Portland cement and they instead prefer to use marine cement.

To make their materials as sustainable as possible, they use carbonated water in their manufacturing process. Carbon dioxide in carbonated water reacts with portlandite in cement and forms calcium carbonate, which in turn fills the pores in the concrete, enhancing its mechanical properties and also capturing carbon.
They are also experimenting with printing in a CO_2 enriched environment to allow the additional carbon capture in their structures.

As sustainability is one of their main goals, they use 50% of natural aggregates while the other 50% comes from recycled concrete. This reportedly reduces CO_2 emissions by 0.13 kg per 1 kg of concrete.

While the choice of aggregates is wide, they propose a couple of those that they have tested in their extensive experiments.

Dolomite sand

Image 26: Dolomite sand as aggregate (source: Coastruction)

Aragonite sand

Image 27: Aragonite sand as aggregate (source: Coastruction)

Quartz sand

Image 28: Quartz sand as aggregate (source: Coastruction)

Beach sand

Image 29: Beach sand as aggregate (source: Coastruction)

Recycled concrete

Image 30: Recycled concrete as aggregate (source: Coastruction)

5.2 Benefits

Coastruction structures have multiple benefits and goals, as stated in their SDG/Sustainability document.

Biodiversity restoration and conservation

As it was covered in chapter 3.2, artificial reefs restore and contribute to biodiversity. Coastruction does this in two ways, one is to use their reefs as a substrate for growing corals – this method was described in chapter 3.1. The second is by naturally attracting corals and other marine species to grow on their reefs.

They conducted a one-year experiment with the Division of Aquatic Resources in Hawaii where they planted corals on their 3D-printed artificial reef. Coral growth can be seen in the image below where in just one year coral larval settlement has covered a majority of the structure.

Image 31: Coral larval settlement (source: Coastruction)

Coastal protection

A common benefit of artificial reefs is coastal protection. Coastruction structures can help reduce wave energy by 72%, reducing coastal floods and, therefore, preventing deaths by flooding and promoting annual savings from avoided damages.

Local resources

As stated above, their technology promotes the use of natural and local materials for aggregates, reducing emissions from transport and packaging, while also preventing the introduction of non-native materials in the water.

Other species

Artificial reefs can provide shelter for over 4000 species of fish and invertebrates. A good example of this was one of the Coastruction projects in the Netherlands. The Oostvorne Lake is considered ecologically challenged with poor aquatic life.

The project aimed to establish a biodiversity-rich habitat and improve the ecological quality of floating wind turbine anchors, which are concrete blocks that exhibited little to no life. This project shows the benefit of 3D-printed artificial reefs and freedom of design in detail.

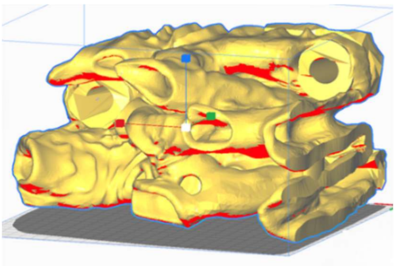

Image 32: CAD model for Oostvorne lake (source: Coastruction)

With input from stakeholders in the form of collaborative workshops, structures with similarities to local nature were designed. They featured holes and crevices which are naturally used by local species as their habitats.

Printing was done with locally-sourced materials Like sand and water from the lake, along with oyster shells from local restaurants.

Within four months, structures were populated by local wildlife, such as gobies, crabs, shrimp, and other organisms. Not only do these results support the advantages of artificial reefs for enhancing biodiversity but also prove the importance of structure complexity for the success of such installations. Concrete blocks (wind turbine anchors) have previously not shown any benefit in providing a habitat for local species, supporting the arguments that many classic (smooth surface and non-complex structures) artificial reefs are not appropriate. To further support this claim, they performed an eDNA analysis and found that there was a 250% increase in biodiversity compared to concrete blocks.

This project shows that artificial reefs, like Coastruction's, are not only saving corals but also providing habitats for fish and invertebrae in both salt and fresh water.

Image 33: Oostvorne lake project results (source: Coastruction)

Economic and other benefits

Artificial reefs promote tourism by providing diving and snorkeling opportunities, as well as fishing, ecotourism, photography, videography, research, and education. By attracting more tourists, it is likely to increase local income while also employing locals in profiles such as tour guides, instructors, and boat crew.

Artificial structures require production, maintenance, and observation activities from local communities, which are many times located in poor countries. Such communities are presented with educational and financial opportunities by collaborating on restoration projects.

Increased fish populations on artificial reefs will also provide more opportunities for local fishermen, supporting better catches and a higher income.

5.3 Conclusions and Recommendations

After a careful review of provided data from Coastruction on their goals, research, development, approaches, and experiments, we can conclude that they are strictly following the latest best practices for artificial reefs and 3D-printing based on up-to-date research findings that are observed in the first half of the thesis.

In terms of materials, the company is aware of the negative effects of traditional concrete and extensively experiments with alternatives to make their approach more sustainable, using carbonated water, CO_2 enriched environment, and marine cement.
Locally resourced aggregates like sand and crushed seashells further support their sustainable approach by reducing transportation emissions, as well as not introducing non-native materials in marine environments.

Based on the literature review done in chapter 2.4, I suggest that the company also looks into using blended cement, which substitutes part of clinker by mixing other cementitious materials because this could potentially make their binding agent even more sustainable.

They fully exploit 3D-printing processes to achieve custom structures that mimic local marine species' habitats to ensure the best integration in specific environments. As observed in chapters 3.2.1 and 3.2.2, structure complexity and substrate texture are crucial parameters in achieving the most optimal restoration project results.

Their approach to sending printers to project locations significantly reduces transportation costs and emissions, adding to the sustainability of their approach. Additionally, their goal to contribute to local economies by providing new job positions is a previously overlooked aspect of restoration projects that demands further research because it could be one of the factors to support the longevity of such projects and provide an additional initiative for government funding.

While the company's documents have stated they previously used crushed shells as aggregate, I suggest that they also experiment with the use of crushed coral rubble because it had the most favorable results in an experiment observed in chapter 3.2.1.
It is worth mentioning that the mentioned experiment demonstrated the highest number of natural recruits without coral transplanting.

They also use powder bed printing technology, which is more sustainable than extrusion printing, due to the lack of a heated nozzle head. However, I suggest that they could further lower their indirect emissions by powering their printing process with renewable energy resources, such as solar, wind, or nuclear.

However, *Obelix*, their prototype printer for large-scale projects will already include sustainable energy resources since it will be fully off-grid and powered by solar/wind (see Image 25).

After carefully observing their approaches, goals, and previous successful projects, we can classify Coastruction as a good practice example of sustainable 3D-printing for marine ecosystem restoration. Their success can be largely attributed to following previous research conclusions in sustainable materials, restoration projects, technology, and extensive experiments. They also have several successful restoration projects in recent years and have the potential to impact the restoration of marine ecosystems in the future significantly.

An interesting aspect of concrete structures is a physical-chemical process called carbonation where CO_2 is stored in the form of $CaC0_3$. This process is very slow and can take years if not decades but research has shown that the use of RAC can significantly speed up this process. (Silva, Neves, Brito, & Dhir, 2015)
The carbonation process in Coastruction structures could prove to be an effective way of creating carbon sinks and should be further explored (and evaluated), especially since they have already been using recycled aggregate in their final products.

6 Case Study: Urban Reef

Urban Reef is an innovative environmental startup from the Netherlands, whose goal is to take advantage of bioreceptivity to restore urban ecosystems. It was founded by Pierre Oskam, Ph.D., and Max Latour, architects who want to mitigate modern problems like urban heat islands, pollution, and urban sprawl.

While their technology can be used to print numerous structures, they have classified their final products into two categories – *Reef* and *Rain Reef.* First is a labyrinth of habitats, potentially providing homes for a variety of species in an urban setting while the second collects rainwater from a downspout creating a cooler humid environment. They are also working on a *Zoo Reef*, which is a form of *Reef* designed for fountains.

Image 34: Reef (left) and Rain Reef (right)
(source: Urban Reef)

The idea behind these complex structures is to promote the growth of algae, mosses, other plants, and even animal species. The benefits of such structures are backed by results from previous research, some of which are reviewed in Chapter 4.1 and its subchapters, confirming that there is scientific support for the company's claims.

The company is currently performing extensive experiments, both with the choice of material, as well as the technological and design approach. They are mainly focused on tracking the bioreceptive success of their materials, either by the choice of material and its processing, as well as by printing-related specifics – nozzle width, nozzle insert, and structure design.

An example of a *Reef* structure, populated by a biofilm and moss can be seen in the image on the right. The image shows a complex design and multiple printed clay layers, susceptible to natural bioreceptivity in a favorable setting.

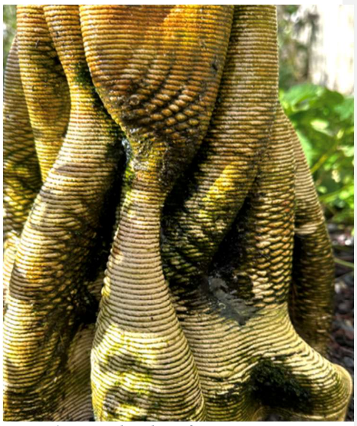

Image 35: Populated Reef
(source: Urban Reef)

6.1 Technology and Materials Testing

Bio-inspired structures are printed using liquid deposition modeling printer (materials extrusion technology), specifically the WASP 40100 LDM (see Image 36), which can print any fluid-dense material (clay, stoneware, earthenware, and porcelain) in dimensions of 400 mm x 450 mm x 1000 mm.
Nozzle diameter can be 1.5 mm, 2 mm, or 3 mm, and layer resolution from 0.5 mm to 5 mm.

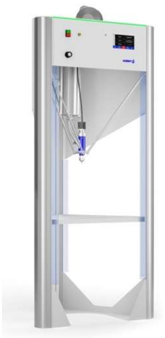

Image 36: WASP 3D printer
(source: https://www.3dwasp.com/)

The design process includes designing structures that are as bioreceptive as possible and creating microclimates that offer essential resources and even shelters for a variety of species.
By using complex computational design, they can create 3D-models that emulate natural habitats where their goal is to target specific species and customize climate conditions, considered favorable by them, such as temperature humidity, and light.

The crucial aspect of the company's design process is interdisciplinary research, actively involving professionals and scholars from a variety of disciplines like biology, architecture, material science, philosophy, business, and even gaming.
Collaboration also includes TU Delft and Utrecht University, giving them essential insights into the needs and behaviors of diverse organisms.

Once a 3D CAD model is created, STL files are uploaded to the LDM printer and the printing process can begin. Materials will be further observed in chapter 6.2 but their go-to material is currently clay. They mix 1.1 liters of water with 20 kilograms of new or recycled clay and then the printing process can start.
After printing, reefs have to dry for 2 weeks before being fired in the kiln. The firing process begins with candling at a maximum temperature of 100 ℃, ensuring that structures are completely dry. Then the firing program starts, by increasing the temperature at 80 ℃ per hour until 600 ℃, followed by a maximum hourly increase until 1070 ℃. Firing at maximum temperature takes only 15 minutes. Then the structures cool down for 24 hours. (Matser, 2023)

Image 37: Printing (left) and firing (right)
(source: Matser, 2023)

Pripombe dodal [MŽ4]: Na prejšnjo stran

Urban Reef is dedicated to researching natural and sustainable materials, such as mycelium, river scallops, shells, clay, river dredge, and also cow dung. One of their main goals when choosing a suitable material is the repurposing of materials destined for disposal, contributing to waste reduction and circular economy. While they do experiment with all of the mentioned materials, they are currently mainly printing final products with locally sourced clay. Clay has high printability potential and porosity, which enables water saturation and evaporation in observed structures.

The importance of bioreceptive surfaces in an urban setting is a novel method, still being actively explored in science. A research paper (Sochůrková et al., 2023), which Dr. Oskam and Latour have co-authored, gives us an insight into an example of extensive research processes that Urban Reef undertakes in search of optimal materials and printing parameters.

The paper observes an experiment comparing clay and river sediment as 3D-printing material for *Reef* structures. Bioreceptivity is split into two categories:

1. external bioreceptivity, and
2. internal bioreceptivity.

The first is the viability of a material for bio-colonization (as explained in Chapter 4.2). The second is a method that implements seeds directly into a 3D-printing paste for them to sprout from the finished product (see Image 38).
In the mentioned experiment, seeds sprouted from raw sediment material in 10 days.


Image 38: Sediment with seeds (left) and clay (right)
(source: Sochůrková et al., 2023)

As was observed before, bio-colonization first starts with algae and cyanobacteria, which require inorganic material to survive while their successors are usually mosses and lichens. Physical and chemical properties are determining factors of successful bio-colonization but also serve as selection criteria for what kind of species migrates to the surface. Roughness and porosity are essential for the attachment of spores and air dust settlement. This is supported by previous research conclusions in chapter 4.2.2.

The bioreceptivity of Urban Reef's structures falls into the quarternary category (see Image 19) by Guillitte's categorization because they treat the outer layer of their final product to kick-start the colonization process. Treatment usually involves the addition of a biofilm. In the observed research paper, Agar and Xantham gum were compared.

The research paper led to a conclusion that lays a solid foundation for future research in urban ecosystem restoration and supports the viability of such projects, as well as providing essential parameters for the success of such projects.

Temperature of firing

Ceramic loses its porosity when it is fired at a higher temperature. Since porosity is essential for high bioreceptivity, firing should be capped at a maximum of 1100 ℃ (in the case of Urban Reef's clay mixture).

Textures

A textured surface provides more area and better conditions for most organisms, allowing them to easily adhere to the surface. The importance of material roughness was x also supported significantly in chapter 4.2.

Morphology

The shape of the structure was a determining factor in moss growth because it preferred shaded and cooler areas on the *Reef*. Less growth was observed on parts directly exposed to the sun. This directly references the microclimate conditions on such reefs which are increased by creating as many cavities as possible to achieve attractive spaces for life.

Porosity

While the porosity of the material was correlated with the firing temperature, it was observed that the addition of materials with higher porosity can also enhance bio-colonization. When sawdust and sediment were added to clay, denser growth was observed.

Porosity was tested and results can be seen in the image on the right (see Image 39). The top left is the least porous material that exhibits the least growth. Porosity is then gradually higher in order top-right, bottom-left, and bottom-right.
Most porous material exhibits the most growth in the observed experiment.

Image 39: Porosity test
(source: Sochůrková et al., 2023)

Biofilms

Experiments have shown that natural bio-colonization was very slow and kickstarting growth by adding biofilms was preferred because it sped up the process and also allowed the choice of vegetation that will be introduced.

Climate

The conditions of the experiments were the most vital aspect because growth is highly affected by its surroundings and climate.

Enhancement of bioreceptivity with the addition of a nutrient layer was also researched in a master's research project at Urban Reef (Matser, 2023). Matser was experimenting with different techniques to enhance the biodiversity and natural succession of *Reef* structures, accelerating moss growth.

Matser performed three types of experiments:
1. field study,
2. accessibility method, and
3. creating biofilms.

In the first category of experiments, natural succession on a *RainReef* was observed in a natural setting (outside). Structures were connected to a downspout and placed on the south and northern sides of a building. The experiment expected to see algae growth within three months.

The second category was a moss cultivation method where buttermilk, vegan yogurt, and beer were used as a nutrient layer. These nutrient layers should lower the pH of the structure which is favorable to mosses. Moss growth was expected in one month from the addition of a supplement layer and moss spores.

Third-category experiments stimulated succession by creating a biofilm of algae on the structure (substrate) to stimulate moss growth. Algae with water, algae with agar, and hydrogel were compared as supplements. Algae was either *Chlorella Vulgaris* or *Arthrospira Platensis.* Moss growth was expected within one month after the addition of moss spores.

Why Matser's experiments are important is that he has done extensive study both indoors and also in an ideal indoor setting (greenhouse). With this approach, the influence of climate parameters could be tested.

The results of the first experiment – the natural succession – provide a lot of insights into the correlation between temperature, humidity, and growth. Both northern and southern testing structures had a positive correlation between humidity and growth.

The temperature seemed to have a negative correlation with the northern structure and no correlation with the southern. There was also no difference in ambient temperature to that of the *RainReef* structures. Compared with previous studies' results, seasons influence the result as humidity measurements were different in previous experiments.
The experiment expected algae growth within 3 months, which was confirmed.

The second experiment – the supplements has shown interesting results. Alpro showed the highest growth of 27.49%, followed by Buttermilk (19.9%). When the experiment was repeated, mosses were first washed and the results were negative for all supplements.

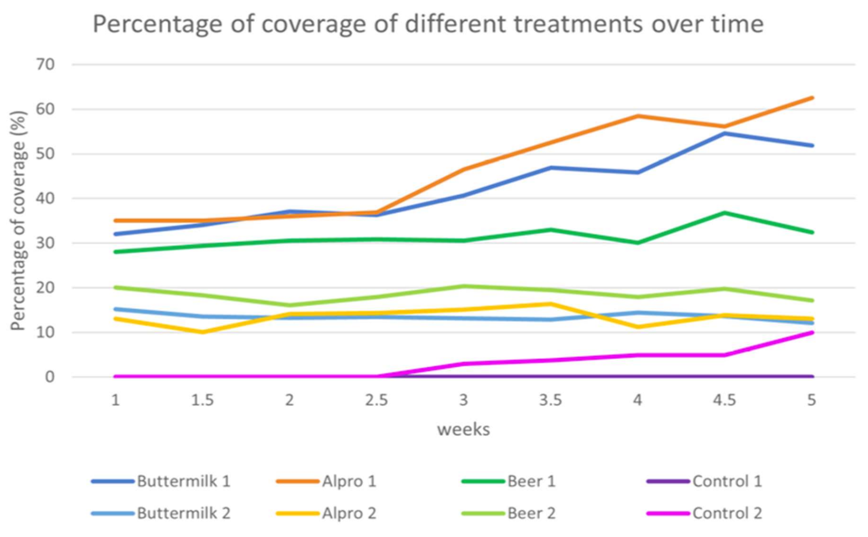

Image 40: Supplement effect on moss growth (source: Matser, 2023)

The third experiment – the biofilm first analyzed which algae (with supplements) showed the highest growth on structures. The difference was traced for 20 days, and interestingly, the highest growth was present in *Chlorella* with water and agar treatment (41.9% and 41.3%, respectively). *Spirulina* with hydrogel and agar showed almost no growth and the hypothesis of moss growth after one month was not confirmed.

After *Chlorella* and agar treatment of 20 days on 6 structures, moss spores were added. After 31 days, green coverage was increased from 6% (day 1) to 26%. While moss growth was difficult to analyze, photos of final growth were provided (see Image 41). Moss growth has taken place and the hypothesis was accepted.

Image 41: Moss growth on Chlorella and agar (source: Matser, 2023)

The project provides also an update after one year since the structures were placed outside. No moss growth was present since the start of the experiment. Therefore, Matsen concluded that the use of a supplement is necessary to speed up the natural succession. He also emphasizes the importance of humidity impact since structures were placed in the Rotterdam docks where humidity is relatively high and another (drier) location could end with different results.

It was concluded that the *RainReef* that Urban Reef produces is already bioreceptive for algae but needs an additional layer to speed up the growth of mosses. For harsher outdoor conditions, more resilient algae research is also necessary.

6.2 Conclusions and Recommendations

After careful examination of Urban Reef's provided information and research documents, we can conclude that they offer a sustainable product for urban ecosystem restoration. Although their structures are still partly in an experimental phase, their extensive research and experimenting, as well as collaboration with academia and various other disciplines, lays a strong foundation for a sustainable approach to restoring urban areas using 3D-printed solutions.

They are actively doing research in a relatively unexplored field of bioreceptivity and bio-colonization where their results are already showing promising results for the success of such projects. They solve difficult issues in urban ecosystem restoration projects, such as slow natural bio-colonization, low natural succession, and effects of climate on growth and variety of different species.
Their approach to using integrated seeds in printing paste (sediment) is very innovative and should be explored more because it could be more supportive of natural succession.

The company is aware of certain negative effects of clay. In this field, they try to always use either local or recycled clay to make it more sustainable. They also experiment with natural materials, such as river sediment, cow dung, and shells, although clay has proved to be the most appropriate material for 3D-printing so far.

Based on the literature review done in chapters 2.3 and 2.5, we can suggest a few possible solutions to make Urban Reef structures even more sustainable.

Printing technology is not very energy intensive, since the printer does not have a heated extrusion nozzle and is therefore quite sustainable already. However, the clay firing process is a very energy-intensive process, which the company can mitigate by using renewable energy resources, such as solar or wind, to power the oven.

While locally sourced or recycled clay are the more sustainable options of clay, using materials that either do not require firing or require firing at lower temperatures could also solve the energy consumption issue of firing oven. These materials are often more fragile but Urban Reef structures are not used in construction and therefore lower material strength should not have an effect on them.

A research paper (Rett, Yannick Leandre Traore, & Ho, 2021) reviewed in chapter 2.3 explored cellulose-based printing materials that require drying at room temperature or drying at temperatures below 100 ℃. Such cellulose-based materials could be of interest to Urban Reef but it would require additional experimenting and also research into water-resistant cellulose materials.

The company states that the primary goal of its solutions is solving urban heat islands, pollution, and urban sprawl. A review of past research in Chapter 4.1 confirms that green urban structures truly have a positive effect on all of those. However, we believe that Urban Reef's structures have even more potential benefits for urban areas.

Their solutions could also improve noise pollution if placed on roofs since green roofs reduce sound transmission. *RainReef* has a very high potential in greywater treatment (filtration) while its water retention properties could solve issues of sewage system overflow during high rain seasons.

The company could design another structure specifically for photovoltaics. Placing green structures below photovoltaics has been shown to increase their performance by 3.35%

(Manso, Teotónio, Silva, and Oliveira Cruz, 2021). Therefore, such custom solutions could be of high interest in the photovoltaics industry.

Similarly to the previous case study of Coastruction, we can also classify Urban Reef as a good practice example of sustainable 3D-printing for urban ecosystem restoration. They do highly innovative research and development in their field and actively collaborate with experts who help them create structures to support biodiversity in urban areas. Their structures have a very high potential for solving multiple urban issues and making life in cities healthier and more enjoyable.

However, additional research is needed to evaluate the impact of Urban Reef's bioreceptive structures on general biodiversity in urban settings. This should be done using long-term studies, ideally in different urban settings that track species colonization. Collaboration with ecologists and experts should be done with the goal of a comprehensive understanding of how 3D-printed structures contribute to urban biodiversity and how this can be quantified.

Similarly to a final recommendation in the previous case study (chapter 5.3), it is recommended that Urban Reef structures are further explored from a carbon sink aspect, and the CO_2 sequestration capabilities of clay and ceramics are evaluated.

7 Results

This chapter presents the findings from the investigation into sustainable 3D-printing technologies, environmentally friendly materials, and their application in ecosystem restoration. Results are based on a comprehensive literature review, supported by practical examples in the form of case studies.

As the case studies analyzed in this thesis are based on secondary sources, particularly published materials and articles, the findings are interpretive in nature and limited by the availability of existing data.

7.1 Key Takeaways

7.1.1 Sustainable 3D-printing

While PLA 3D-printing, the most widespread approach, is not sustainable and has multiple negative environmental effects (marine eutrophication, freshwater eutrophication, human toxicity, and excessive energy consumption), there is a sustainable and environmentally friendly 3D-printing approach.

To ensure the sustainability of this novel technology, two fundamental aspects should always be considered – energy use and material sustainability.
Energy use especially relates to the high power consumption of heated extrusion nozzles in FDM printers, which can be mitigated by using alternative binder jetting or liquid deposition, which does not require heated extrusion and is, therefore, much more energy efficient.
To further ensure the sustainability of 3D-printing technology, energy production should come from renewable energy resources, such as wind and solar.

Sustainable and environmentally friendly materials can be selected by the following criteria:
1. no toxicity (environmental or human),
2. low or no need for high extrusion temperature,
3. energy-efficient curing process, and
4. sustainable material production.

Past research (Faludi, Van, Shi, Bower & Brooks, 2019) has tested materials that follow the above criteria by choosing bio-degradable and natural materials that bond or solidify at room temperature. Among various tested materials (see Chapter 2.3), a paste made of pecan shell flour, water, and sodium silicate performed best. A 75% reduction in printing energy was achieved, as well as an 82% reduction in material impact.

It is also important to ensure sustainable transportation of either 3D-printers or finished products to the target location. This includes the packaging material, mode of transport, logistics, and storage.

To ensure that chosen materials are as sustainable as possible, a life cycle assessment should always be performed. By performing LCA analysis, we can analyze and evaluate the entire life cycle of material, from production to disposal, and all related processes in between.

7.1.2 Marine Ecosystems Restoration

The biggest issue in marine restoration projects is their cost where the median restoration cost was 80,000 $/ha while the average cost was 160,000 $/ha. The total project cost was between

150,000-400,000 $/ha, which is usually funded by a combination of public and private initiatives. (Bayraktarov et al., 2016)

Since more than 60% of the world's coral reefs are under immediate threat, they are one of the most popular marine restoration projects. The most common approach is introducing artificial reefs to degraded habitats where corals are either transplanted to artificial structures or a substrate stabilization/enhancement provides an appropriate surface for natural coral larvae attachment.

Past research (see Chapter 3.2.1) has identified that two structure parameters are crucial for the success of artificial reefs for restoration initiatives – structure complexity and substrate material. The best approach in such projects is, therefore, creating a structure with high complexity where the substrate layer (top layer) of the structure should be coarse or, ideally, made from coral rubble.

There are multiple issues with existing approaches to artificial reefs. The material of choice is usually smooth concrete, steel (sunken ships), or rubber tires. These are made of smooth surface shapes which are not ideal for coral attachment, while rubber tires also present an environmental hazard.

Another issue is project monitoring and size. 60% of all restoration projects had less than 18 months of monitoring of restored sites while the median size of projects was 100 square meters. From such a short period of time and scale, it is difficult to evaluate the restoration success because it means by definition that a restored ecosystem *contains sufficient biotic and abiotic resources to continue its development without further assistance or subsidy.*

3D-printing technology can significantly improve the potential for the success of artificial reefs because it enables the creation of custom-made solutions with complete control over structure complexity and surface roughness, as well as material choice. Printing with concrete is possible in both binder jetting and liquid deposition. To make it more environmentally friendly, one of the more sustainable concrete alternatives can be used, such as blended cement, or even other appropriate materials.

Another important feature of 3D-printing is mitigating transportation-related emissions and packaging waste because structures can be printed on-site while also using locally sourced materials for production. This in turn also supports the local economy by providing jobs to locals.

7.1.3 Urban Ecosystems Restoration

Addressing the negative effects of urbanization is becoming increasingly important in research and urban design. The most common approach is introducing green urban structures into cities, such as green roofs and walls.
These structures have numerous benefits:
1. reduced energy consumption (additional insulation),
2. higher photovoltaic performance (when placed below solar panels),
3. sound transmission reduction,
4. greywater treatment,
5. urban heat island effect mitigation,
6. water retention capacity,
7. runoff water quality,
8. air pollutant sequestration, and
9. carbon-dioxide consumption.

In terms of carbon dioxide consumption, structure material can act as a primary source of carbon storage while growth (moss, lichen, and bio-film) can act as a secondary source of carbon storage. More porous structure materials have a higher storage potential.

Additionally, green structures and roofs can provide non-quantifiable benefits, such as promoting health and well-being, contributing to mental and physical health, as well as stress alleviation.

A big focus of this thesis was bioreceptivity – the ability of a material to be colonized by one or several groups of living organisms. Recently, researchers have been exploring a shift in perceiving greening of building surfaces from negative to positive. Instead, enhancing bioreceptivity of concrete is researched to add more green to cities potentially and provide above mentioned benefits.
While the primary bioreceptivity of concrete is quite low, we have the means to enhance it. Interestingly, similarly to artificial reefs, enhancing bioreceptivity is also done by material choice, increased complexity, and surface roughness while higher water-retention properties are also of great importance.

As previously mentioned, 3D-printing can create custom complex structures from a large array of materials. Computer modeling can be used to control water diffusion and channeling in produced structures, creating bioreceptive solutions. Increasing porosity can be done by using a wider nozzle and increasing layer height (see Chapter 4.2.2). With computer modeling, complex structures can be created to support targeted species growth, such as moss.

7.1.4 Coastruction

Coastruction is a good practice example of sustainable marine ecosystem restoration. Their approach is heavily based on following advice from previous research where we also concluded that they follow most of the recommendations from the first part of this thesis – literature review (see Chapter 3).

They have developed an in-house custom powder bed printer (binder jet). As previously mentioned, this technology does not require a heated extrusion nozzle and is, therefore, more energy efficient. Additionally, all of the unused material from the printing area can be reused for future prints.

While the main material of choice is cement, however, they are familiar with the negative environmental impact of traditional (Portland) cement and instead prefer to use marine cement. They further reduce CO_2 emissions by using carbonated water in their manufacturing process, and they are also experimenting with CO_2 enriched environment printing. Additionally, 50% of natural aggregates are used while the remaining 50% come from recycled concrete. This reportedly reduces CO_2 emissions by 0.13 kg per 1 kg of concrete.

One of the most important aspects of their work is the use of natural and local aggregates. They can print with a large variety of local materials like dolomite sand, aragonite sand, quartz sand, and beach sand. As they print on-site, this in turn also reduces emissions and waste associated with the packaging and transportation of materials while also supporting local communities with job opportunities.

While they do specialize in artificial reefs, they also target other marine restoration projects (fish and invertebrae), most notably the Oostvorne Lake restoration project (see Chapter 5.2). When designing their structures, they collaborate with experts to target specific species and provide them with an appropriate habitat.

Their approach supports the importance of doing extensive research and experimentation before starting restoration projects, as this improves the chances of project success significantly.

Table 4: Coastruction Key Takeaways

Aspect	Explanation
Research-Based Approach	It follows recommendations and best practices from past research.
Technology Used	Binder jetting.
Energy Efficiency	No heated extrusion nozzle.
Material Reuse	Unused (unbound) material from the powder bed is reused for new prints.
CO_2 Emissions Reduction	Carbonated water approach, CO_2 enriched environment experimentation and 50% RAC use.
Local Materials	The use of domestic materials reduces transportation costs and enables on-site printing.
Job Opportunities	Supports local communities by creating new job opportunities.
Collaborative Design	Collaboration with experts ensures best practices and can target specific species and goals.
Research and Experiments	They do extensive research and experimentation, which increases the chances of project success.

7.1.5 Urban Reef

Urban Reef is also an example of a good practice approach but they restore urban ecosystems by creating artificial highly bioreceptive structures. As in a previous case study, they too have done extensive research and also collaborate closely with other fields to maximize the success of their restoration projects.

They use a liquid deposition modeling printer, which also does not require a heated extrusion nozzle. However, they print with clay which needs to go through a firing sequence to cure the printed product and this process is quite energy intensive but they are currently in an experimental phase and aware of the issue.

Sustainability is their target and they are heavily focused on using environmentally friendly clay because they usually print with locally sourced or even recycled clay. They also perform experiments with alternative natural materials, such as mycelium, river scallops, shells, clay, river dredge, and cow dung. One of their primary goals is to use materials destined for disposal to contribute to waste reduction and circular economy.

They focus heavily on bioreceptivity where a lot of their approaches overlap with key findings in the literature review part of this thesis (see Chapter 4.2). As previously mentioned, natural biocolonization is a rather slow process and one of Urban Reef's targets is trying to solve this issue.
Their firing process at a maximum of 1100 ℃ ensures that structures have high porosity while their structures also have high structural complexity. To speed up the biocolonization, they experiment with various treatments of the outer layer by adding a biofilm or supplements

(buttermilk, Alpro, beer, etc.). They can even integrate seeds into the printing paste, which later sprouts from the final structure.

Similarly to Coastruction, their approach also supports the importance of performing research and experiments. To ensure eco-friendly approaches, it is recommended that they use LCA analysis for their printing materials while also exploring clay alternatives that can cure at lower temperatures.

Table 5: Coastruction Key Takeaways

Aspect	Explanation
Research-Based Approach	It does extensive research and follows best practices.
Technology Used	Liquid deposition modeling printer.
Energy Efficiency	No heated extrusion nozzle. However, the firing process is energy-intensive.
Material Focus	Either locally sourced clay or recycled clay.
Bioreceptivity Focus	Maximizing bioreceptivity through firing sequences, material choice, and upper layer treatment.
Experimental Materials	Experimenting with alternative natural materials.
Interdisciplinary Collaboration	Collaboration with other fields maximizes the success of restoration projects.
Biocolonization Acceleration	Experimenting with upper layer treatments to accelerate biocolonization.

7.2 Hypothesis

Table 6: Hypothesis Acceptance

Hypothesis	Acceptance
H1	Accepted
H2	Cannot be fully accepted
H3	Accepted

7.2.1 Hypothesis 1

Based on findings from the literature review in chapters 3.2.1, and 3.2.2 and the case study in chapter 5, we can **accept** hypothesis 1 – 3D-printed solutions show a higher recruitment of marine organisms compared to conventional solutions.

Structure complexity and substratum material are very important parameters in artificial reefs. 3D printing and computational design support the creation of custom complex structures from various materials with optimized physical and chemical properties.

7.2.2 Hypothesis 2

Based on the literature review in chapter 4.2.2 and the case study in chapter 6, we **cannot fully accept the** hypothesis that 2 – 3D-printed solutions increase biodiversity in urban areas.

Previous research and results from Urban Reef show promising outcomes of 3D-printing by creating highly bioreceptive structures. While bio-colonization of such structures with algae and moss was successful, further research is needed to prove a direct impact on biodiversity. Long-term, large-scale experiments in urban areas are needed where biodiversity indicators should be observed.

7.2.3 Hypothesis 3

Based on the literature review in chapters 2.2 and 2.3, as well as case studies in chapters 5 and 6, we can **accept** hypothesis 3 – Natural or recycled 3D-printing materials have a lower environmental impact compared to conventional polymer filaments.

While most common PLA extrusion 3D-printing is not environmentally friendly, there is available technology that is. The use of natural and non-toxic materials, combined with renewable energy-powered 3D-printers that do not have a heated extrusion nozzle, has a very low environmental impact. LCA analysis of printing materials should be done to find those that have the lowest environmental impact.

7.3 Research Questions

7.3.1 Research Question 1

What impact do 3D-printed solutions for the restoration of marine and urban ecosystems have on biodiversity?

3D-printed solutions have a large potential to have a positive impact on biodiversity in marine and urban ecosystem restoration projects. One of the key identified parameters for the success of both marine and urban projects was **structure complexity** and **surface porosity**. 3D-printing technology enables the creation of custom complex structures, targeting specific species for rehabilitation. The porosity of the structure can also be controlled due to a large array of material options that printers can print with.

7.3.2 Research Question 2

What general ecological impact do 3D-printed solutions for the restoration of marine and urban ecosystems have?

The 3D-printing process can be sustainable and also enables the use of environmentally friendly materials (local materials, recycled materials, bio-based materials, etc.). If the sustainability of both the process and materials is taken into account, 3D-printed solutions can have a positive ecological impact because they can be a tool for ecosystem restoration and rehabilitation.

7.3.3 Research Question 3

How can we ensure that 3D-printed solutions for the restoration of marine and terrestrial ecosystems are sustainable, environmentally friendly, and best utilized?

Ensuring sustainability, environmental friendliness, and correct utilization of 3D-printing is heavily dependent on specific restoration targets.
In general, the 3D-printing process can be sustainable by using 3D-printers without a heated extrusion nozzle, such as binder jet printers and liquid deposition modeling printers. To make the process fully sustainable, the printer should be powered by a renewable energy source.

When choosing materials, a detailed LCA analysis can provide insights into the material's environmental impact from production to disposal. In general, locally sourced and natural materials should be used when possible.
Additionally, it is important to take into account the possible need for a curing sequence (firing). In that case, materials should be replaced with alternatives (and binders) that can cure at room temperature.

To best utilize the 3D-printing technology, a detailed review of previous research should be done, as well as a close collaboration with the experts. This can result in the use of more appropriate materials, design of sufficient structural shape and complexity, and also target specific species that demand rehabilitation.

8 Conclusion

The thesis focused on the application of 3D-printing technology for the restoration of marine and urban ecosystems, assessing both the technology's benefits and environmental impact. While the broader topic encompasses many subfields, this research specifically concentrated on coral reefs and urban bioreceptive structures, using these as focal points to explore how 3D-printing can support ecosystem rehabilitation.

While marine and urban ecosystems and their restoration are very broad terms, the thesis primarily focused on coral reefs and urban bioreceptive structures. Studies indicate that both artificial coral reefs and urban bioreceptive structures demand two main parameters that increase their success – structure complexity and surface roughness (and porosity).

One of the main conclusions of 3D-printing assessment is that it offers numerous advantages to both marine and urban ecosystem restoration, compared to traditional manufacturing of similar structures. Its ability to print with a large variety of different materials is considered a big advantage.
In both urban and marine settings, this technology allows for custom-made solutions with high complexity, and surface roughness and porosity. Additionally, computational modeling can be used to target specific species in restoration and rehabilitation efforts.

In marine applications, printed structures ease the attachment of coral larvae, while also increasing the biodiversity of other species, which was shown in the Coastruction's Oostvorne lake restoration project.
In urban settings, 3D-printing can be used to increase the bioreceptivity of created structures. Natural biocolonization was found to be very slow but Urban Reef has identified solutions to this issue. Either a biofilm or a supplement layer can be added to the structure which in turn speeds up the process of colonization. However, the effectiveness of urban solutions in increasing biodiversity requires further long-term and large-scale research.

While the most common form of 3D-printing, PLA FDM printing, is not environmentally friendly and can even be toxic, there are ways to ensure the sustainability of this technology and minimize the negative environmental impacts.
The printing process with a heated extrusion nozzle is a very energy-intensive process. Therefore, binder jetting and liquid deposition modeling are two of the more energy-efficient types. The use of renewable energy sources can even further lower their impact.

Material choice is the most important thing to consider when using 3D-printers. Life cycle assessment (LCA) is an essential tool in assessing potential materials for printing because it evaluates the material's impact from production to disposal. There are alternative natural materials that have been successfully used in research experiments, which are cured at either room temperature or require a low firing temperature sequence.

However, for a comprehensive sustainability evaluation, it is necessary to also consider life cycle costing (LCC) and social life cycle assessment (SLCA) to address economic and social dimensions. While the thesis focuses on environmental assessment through LCA, incorporating LCC and SLCA is recommended for future studies.

In conclusion, 3D-printing technology was found to be of great potential for ecosystem restoration projects, both in marine and urban settings. The thesis highlights the importance of matching design parameters to ecological function and of selecting materials and methods with minimal environmental impact. With interdisciplinary collaboration and a commitment to sustainability, 3D-printing can be a valuable tool in restoring degraded ecosystems and enhancing biodiversity. Future research should focus on long-term and large-scale experiments in urban and marine ecosystems, using the identified guidelines and parameters, to evaluate 3D-printing technology's positive impact on both the environment and society.

9 Summary

In recent years, 3D-printing has gained popularity in being applied as a tool for creating complex and customizable solutions for ecosystem restoration. Its ability to produce objects from a wide range of materials has shown great potential in such projects and could even provide a cheaper and more effective alternative to traditional approaches. However, the sustainability of 3D-printing remains a concern and should be thoroughly evaluated.

The purpose of this thesis is to evaluate the impact of 3D-printed solutions on the biodiversity of marine and urban ecosystems and asses the ecological impact of such solutions. A secondary purpose of the thesis is to identify key parameters that influence the suitability of these solutions, as well as to provide the guidelines for ensuring their sustainability and environmental friendliness in ecosystem restoration projects.

In the first part, a thorough analysis of 3D-printing technology and its sustainability is done in the form of a literature review. Energy consumption is the main concern where heated nozzles (material extrusion) and curing process (binder jetting) are its largest contributors. Finding sustainable materials is essential and life cycle assessment is identified as an important approach for cradle-to-grave evaluation of potential filament material.

As a part of the literature review, marine and urban ecosystem restoration efforts are evaluated, both in traditional aspects, as well as in relation to additive manufacturing. The main focus is on artificial coral reefs (marine setting) and bioreceptive structures (urban setting). It is identified that one of the key parameters in both applications is structure complexity, substrate material, and surface morphology, all of which can be modified and optimized using 3D-printing technology.

The second part of the thesis includes two case studies. First is a marine restoration startup Coastruction, which focuses on creating artificial reefs using locally sourced materials and sustainable approaches, like binder jetting, enabling them to create complex habitats for increasing biodiversity in marine environments. The second is of an urban restoration startup Urban Reef, which develops bioreceptive clay structures that could mitigate the negative effects of urbanization. They are heavily focused on bioreceptivity and on speeding up the process of biocolonization.
Both startups are identified as best practice examples of additive manufacturing use for ecosystem restoration and the results of the case studies represent a strong foundation for the identification of key parameters and guidelines for the sustainable use of 3D-printing technology in restoration efforts.

The thesis concludes that 3D-printing represents great potential for a novel approach to marine and urban ecosystem restoration. Its ability to create complex structures from a wide variety of materials is a viable alternative to traditional restoration methods. Key findings of the thesis indicate that the main concerns about sustainability are related to energy consumption and material selection, which need to be addressed.

It is essential to choose energy-efficient printing methods, such as binder jetting and liquid deposition modeling where additional attention also needs to be put on the energy intensity of the curing process. Adopting sustainable materials, like recycled or bio-based materials, is crucial for minimizing the ecological impact of printing. Additionally, the toxicity of materials used in restoration projects must be subject to detailed analysis to ensure they do not pose a threat to the environment. Life cycle assessment was identified to be the recommended approach to finding suitable filaments.

Case studies of Coastruction and Urban Reef illustrate the significance of detailed research, experimentation, and interdisciplinary collaboration for ensuring the sustainability and success of restoration projects. Integrating scientific knowledge with 3D printing can be used to create adaptive solutions that target specific challenges in marine and urban ecosystems.

10 Povzetek

V zadnjih letih je 3D-tiskanje postalo priljubljeno orodje za ustvarjanje kompleksnih in prilagodljivih rešitev obnove ekosistemov. Sposobnost izdelave predmetov iz širokega nabora materialov je pokazala velik potencial pri takšnih projektih in bi lahko predstavljala cenejšo in učinkovitejšo alternativo tradicionalnim pristopom. Kljub temu pa ostaja trajnost 3D tiskanja zaskrbljujoča in neraziskana tema, ki jo je potrebno podrobno oceniti.

Namen tega dela je oceniti vpliv 3D-tiskanih rešitev za izboljšanje biodiverzitete morskih in urbanih ekosistemov ter ovrednotiti ekološki vpliv takšnih rešitev. Sekundarni namen dela je identificiranje ključnih parametrov, ki vplivajo na primernost omenjenih rešitev in hkrati zagotoviti smernice za zagotavljanje trajnostnih in okolju prijaznih obnovitvenih projektov.

V prvem delu je v sklopu pregleda literature opravljena podrobna analiza tehnologije 3D-tiskanja in njene trajnosti. Glavni problem je poraba energije, kjer največ prispevajo ogrevane šobe in postopki strjevanja. Iskanje trajnostnih materialov je bistvenega pomena; analiza življenjskega cikla (LCA) se je pokazala kot pomemben pristop pri izbiri potencialnih materialov tiskanja.

V sklopu pregleda literature so ocenjeni tudi pristopi obnove morskih in urbanih ekosistemov, tako tradicionalnih kot tudi tistih, povezanih z aditivno proizvodnjo. Glavni poudarek je na umetnih koralnih grebenih (morsko okolje) in bioreceptivnih strukturah (urbano okolje). Ugotovljeno je, da so ključni parametri struktur v obeh okolij strukturna kompleksnost, material substrata in morfologija površine, ki jih lahko prilagajamo in optimiziramo z uporabo tehnologije 3D-tiskanja.

Drugi del vključuje dve študiji primera. Prva preučuje startup Coastraction, ki je osredotočen na proizvodnjo umetnih grebenov; pri tem uporabljajo lokalne materiale in trajnostno 3D-tiskanje (brizganje veziva), kar jim omogoča proizvodnjo kompleksnih habitatov za izboljšanje biodiverzitete v vodnih okoljih. Druga pa preučuje startup Urban Reef, ki izdeluje glinaste bioreceptivne strukture za obnovo urbanih ekosistemov in preprečevanje negativnih vplivov urbanizacije. Podjetje se močno osredotoča na bioreceptivnost in pospeševanje procesa biokolonizacije materialov.
Obe podjetji sta identificirani kot primera dobre prakse aditivne proizvodnje za obnovo ekosistemov; rezultati študij predstavljajo dobro podlago za identifikacijo ključnih parametrov in smernic trajnostne uporabe 3D-tiskanja pri obnovitvenih projektih.

Delo ugotavlja, da ima 3D-tiskanje visok potencial kot nov pristop k obnovi morskih in urbanih ekosistemov. Sposobnost ustvarjanja kompleksnih struktur iz širokega nabora materialov je izvedljiva alternativa tradicionalnim pristopom obnove. Ključne ugotovitve dela kažejo, da so glavne skrbi glede trajnosti v veliki meri povezane s porabo energije in izbiro materialov.

Bistvenega pomena je izbira energetsko učinkovitih metod tiskanja, kot sta brizganje veziva in modeliranje poltekočih slojev; dodatno pozornost je potrebno posvetiti energetski porabi postopka strjevanja. Uporaba trajnostnih materialov, kot so reciklirani in naravni materiali, je ključna za zmanjšanje ekološkega vpliva tiskanja. Dodatno pa je potrebno analizirati toksičnost materialov, uporabljenih v obnovitvenih projektih, ter zagotoviti, da ne predstavljajo okoljskega tveganja. Analiza življenjskega cikla je bila identificirana kot priporočen pristop k iskanju primernih filamentov.

Rezultati študije primerov Coastruction in Urban Reef poudarjajo pomen podrobnega raziskovanja, eksperimentiranja in multidisciplinarnega sodelovanja za zagotavljanje trajnosti in uspeha obnovitvenih projektov. Sodelovanje z znanstveniki pri 3D-tiskanju lahko omogoči ustvarjanje prilagodljivih rešitev, ki ciljajo specifične izzive morskih in urbanih ekosistemov.

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