ARTIFICIAL REEFS

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SARTI UPC

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Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú

UNIVERSITAT POLITÈCNICA DE CATALUNYA

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PREFACE

In front of you is the design briefing on the process and product formation of Artificial reefs with a focus on sustainability and enhancing marine biodiversity. This briefing was written in the context of previous research obtained by different research groups that will be attached on the appendices of this document. From the beginning of February attention has been paid to these projects by means of research, analysis and sketches.

Before we delve into the details of this project, we would like to take a moment to express the sincere gratitude to the teachers of the EPS course because without their encouragement and constructive feedback, this project would not be running.

Our supervisors M. Joaquin DEL RIO, M. Daniel THOMAS and M. Marco FRANCESCANGEIL for accompanying us on the project, giving us advice during the whole semester. We have been fortunate enough to be working with our supervisor's team, whose guidance and support are invaluable throughout the entire process and who are doing their biggest efforts to make the project run as smoothly as possible. Without their help, it would be possible to carry out this project at a high level.

We would also like to thank the OBSEA installations for the opportunity of this project, it has brought a lot of knowledge and experience with it from another industry.

The teachers M. Lluis GIL and M. Ernest BERNAT for hosting us in Terrassa university and giving us advice about our design

The technician lab M. Oscar PEREZ for taking the time to explain the operation of the plastic 3D printing to achieve our first tests.

And finally, the Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú for welcoming us in the university and made us discover the Spain.

SUMMARY

This report is a final report of an EPS project about artificial reefs.

The project is being carried out by four engineering students who are studying at Universitat Politécnica de Catalunya in Vilanova I La Geltrù. The aim of the project, which began on February 8th, is to design an artificial reef to restore the flora and fauna in a specific area near a marine observatory established by the company SARTI. The report outlines the methodology used to carry out the project during these months of work, which involved research on the existing fauna in the targeted area (fish and crustacean species), creation and analysis of 3D designs, simulation of the different models and other processes in order to create the most suitable design. The report also contains market and competitive research as well as the analysis of different materials. Overall, the report provides a detailed overview of the two models of artificial reefs that have been created to restore the marine environment.

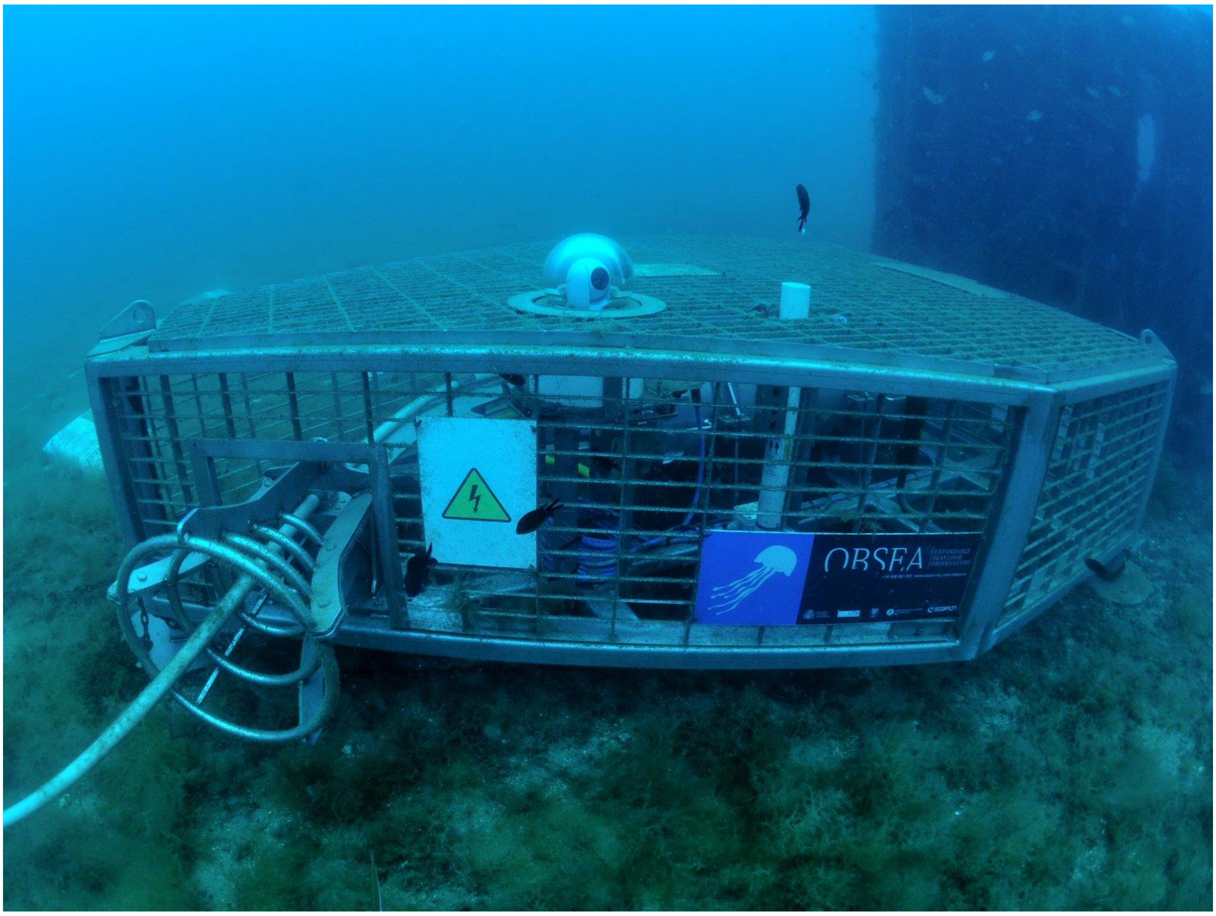

Figure 1: OBSEA center SARTI

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1. INTRODUCTION

1.1 Team introduction

The project is carried out by a team made up of four different students from different backgrounds.

Emma Cañavate is a last year mechanical engineering student in Universitat Politècnica de Catalunya in Vilanova i La Geltrú. Some of the qualities involved with her studies are the technical knowledge and skills such as a strong foundation in mechanical engineering principles, including thermodynamics, fluid mechanics, materials science, and dynamics. Moreover, this also relates to experience on using relevant software and tools for design, analysis, and simulation, such as the ones using during the project. As a conclusion, her background also can provide the ability to apply engineering concepts to solve complex problems and propose innovative solutions during the project.

Kim de Haan has a background in industrial product design and comes from the Netherlands. The background is an asset to the team in the field of design. Several skills that come under this include: having knowledge of 3D printing which gives good insight into what can and cannot be produced with a 3D printer, in addition, modelling in a 3D CAD programme is no problem and a model can be set up quickly in a programme such as Solid Works. This also involves knowledge about combinations of different materials and production processes where the properties of the materials can influence which process. Finally, since there is also a lot of design and shaping involved, a good designed, orderly report and presentation can be created.

Lucie Dzuirka, a native of France, possesses a strong background in packaging engineering. With her expertise in project management and past experiences, she has gained valuable insights into effective project execution. Furthermore, her work in these areas has enabled her to develop proficiency in 3D design. In addition to her engineering studies, Lucie also has a solid foundation in physics, which greatly aids her in making accurate calculations. She possesses excellent public speaking abilities. She is comfortable addressing large audiences and effectively conveying her ideas and expertise. This valuable skill allows her to confidently engage and communicate with a wide range of individuals in various professional settings.

Yassine El Hajji, a dedicated engineering student from France, contributes a diverse skill set to the team working on the artificial reef design project. With a diligent approach to research and calculations, he effectively analyses and solves intricate problems. Yassine's enthusiasm for learning extends to exploring different materials, enhancing his understanding in this area. Moreover, his creativity and attention to detail allow him to produce visually appealing and well-organized reports and presentations.

1.2 The role of artificial reefs in marine conservation

Artificial reefs have become increasingly popular in recent years as a way to enhance marine biodiversity and promote sustainable fishing practices. These are man-made structures that are designed to mimic the natural habitat of marine organisms. They are typically made of materials such as concrete, steel, or stone and are strategically placed in areas where marine life is scarce or damaged. The main goal of artificial reefs is to create new habitats that can support a diverse range of marine species and promote sustainable fishing practices. [1]

Designing and implementing a new artificial reef involves careful consideration of several factors. It is also important to consider the potential environmental impacts of the reef and to ensure that it does not cause unintended harm to the surrounding ecosystem. The installation of artificial reefs in Vilanova I la Geltrú is part of a larger effort to restore the ecological health of the local marine ecosystem. Overfishing and pollution have led to a decline in fish populations and a loss of biodiversity in the area. The introduction of artificial reefs aims to address these issues by providing a new habitat for marine life and promoting sustainable fishing practices.

Overall, the installation of artificial reefs in Vilanova I la Geltrú represents a promising new approach to marine conservation and sustainable fishing practices. The project has the potential to significantly enhance the biodiversity of the local marine ecosystem and provide a new source of income for local fishermen. The project is in association with SARTI-MAR Research group at UPC and it will be implanted near the OBSEA cabled observatory at only a few kilometres from the coast of Vilanova i la Geltrú. Indeed, they have an observatory research lab to monitor the sea biodiversity. Due to this surveillance, they are able to provide data about different useful parameters. Moreover, near the OBSEA, there is a protected area which contains a reef. For that reason, the artificial reef will be implemented a little further to extend the biodiversity.

1.3 Evolution and previous projects on Artificial reefs

Before the installation of the artificial reefs in Vilanova I la Geltrú, a number of pilot projects were conducted to test the feasibility of the concept. These projects involved the construction and deployment of small-scale reefs in different areas of the local waters. The success of these pilot projects provided the impetus for the larger-scale installation of artificial reefs throughout the area. The state of the art regarding artificial reefs has evolved considerably over the years. Since their invention in the 1960s, artificial reefs have been widely used worldwide for a variety of applications, ranging from habitat restoration to coastal protection and recreational fishing. Designs for artificial reefs have been improved to reflect the specific needs of local marine species, with different materials used for different applications. New technologies such as 3D printing are also being used to create more sophisticated and effective artificial reefs. The evolution of artificial reef designs has been driven by a growing understanding of the complex ecological relationships that exist within marine ecosystems. Modern artificial reefs are often designed to mimic the natural structures and habitats found in the marine environment, such as coral reefs and rocky outcrops. They may also incorporate specific features that provide habitat for certain species, such as nooks and crannies for small fish and larger openings for larger fish and predators.

1.4 Materials and 3D printing

Advances in materials science have also played a significant role in the development of artificial reefs. The materials used in artificial reefs can have a significant impact on their effectiveness, as well as their environmental impact. For example, some materials are more durable and resistant to degradation than others, while others may be more biodegradable and environmentally friendly. Additionally, some materials may be more suitable for certain applications, such as protecting shorelines from erosion or providing a substrate for the growth of corals and other reef-building organisms.

The use of 3D printing has opened up new possibilities in the design and construction of artificial reefs. This technology allows for the creation of complex shapes and structures that can more closely mimic the natural structures found in the marine environment. 3D printing also enables the use of materials that may have been difficult or impossible to use in traditional manufacturing processes, such as recycled plastics or biodegradable materials. Overall, the evolution of artificial reef designs and materials has led to more effective and sustainable solutions for restoring marine habitats and promoting biodiversity. However, it is important to continue to monitor and evaluate the environmental impact of artificial reefs to ensure that they are being used in a responsible and sustainable manner.

Figure 2: Previous artificial reef SARTI

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2. ORIENTATION PHASE

The orientation phase of the report contains the following elements: Introduction to the main research steps covered in the phase, as well as the various sub-research studies that have been done for orientation to the design issue. This can be research for general orientation, or specifically for the purpose of the brief, the idea phase or the concept phase. This research provides many insights that can be important in the idea generation.

2.1 Company

The project is been conducted in association with SARTI-MAR *"Centre de Desenvolupament Tecnològic de Sistemes d'Adquisició Remota i Tractament de la Informació"* Research group formed by personnel from different departments of the UPC. SARTI-MAR is focused on scientific and technological development of remote data acquisition equipment and systems, emphasising virtual and oceanographic instrumentation, including simulation methods and statistical analysis, and using cutting-edge techniques in electronic design. Their goal is to enhance society's progress and boost companies' competitiveness through the creation of instrumentation technologies and intelligent sensor systems. The company has two main objectives: to provide its solutions across all industrial and productive sectors, and to specialize in the marine environment. SARTI strives for excellence in its work by adhering to high-quality standards.

Figure 3: Logo SARTI

Moreover, the research conducted at the OBSEA, an underwater laboratory located four kilometers from Vilanova beach and twenty meters deep, aims to collect information on various environmental parameters. This data is used to study the effects of climate change. Having this infrastructure, the fact that it is one of the few wired observatories that exist and that therefore allows data to be obtained in real time, has led SARTI to be part of several European projects since 2014.

Their previous projects are focused on developing the next generation of scientific instrumentation tools and methods for sensing marine-life. In addition, analysing the performance of different materials. One of their most recent works is focused on 3D slag concrete manufacturing solutions for marine biotopes. This is directly the EPS Artificial Reef project as the main goal of their studies will be the manufacturing of artificial reefs for marine biotopes using a large-scale 3D printer. The printed material will be concrete with slag aggregates from waste residues of the steel industry, together with calcareous quarry waste.

As a conclusion, their objectives are to address a circular economy solution for slag furnace and quarry waste residues, foster 3D printing large scale automation and digital solutions, developing new seafloor structures compatible with advanced ecological monitoring systems and tools for the assessment of artificial reefs potential at restoration in order to accelerate the restoration of damaged coastal ecosystems with standard, highly-replicable redeployed units and more important, to protect coastal environments from climate change.

2.2 Project Brief

The main goal of the project is to design and prototype an artificial reef using 3D printers with sustainable materials and methodologies. In order to choose the right material, some parameters need to take into account such as the waste generated and the cost of production.

The main objectives are oriented to:

- Address a circular economy solution for quarry waste residues.
- Develop a new seafloor monitoring system and tools for the assessment of artificial reefs.
- Solve restoration of damaged ecosystems.
- Protect coastal environment from climate change.
- Foster 3D printing large scale automation and digital solutions.
- Provide research for the future and come up with innovative ideas.

The project will design new procedures for artificial reefs manufacturing and its assessment that would be exploited in future projects oriented to habitat restoration.

- Design artificial reef prototypes from new concrete mixtures. Work will need to be done to ensure that laboratory-designed mixtures are feasible for the manufacture of shapes and structures, such as those required for artificial submarine reef formation.
- To study economic viability of the products and to study the market place and future opportunities.

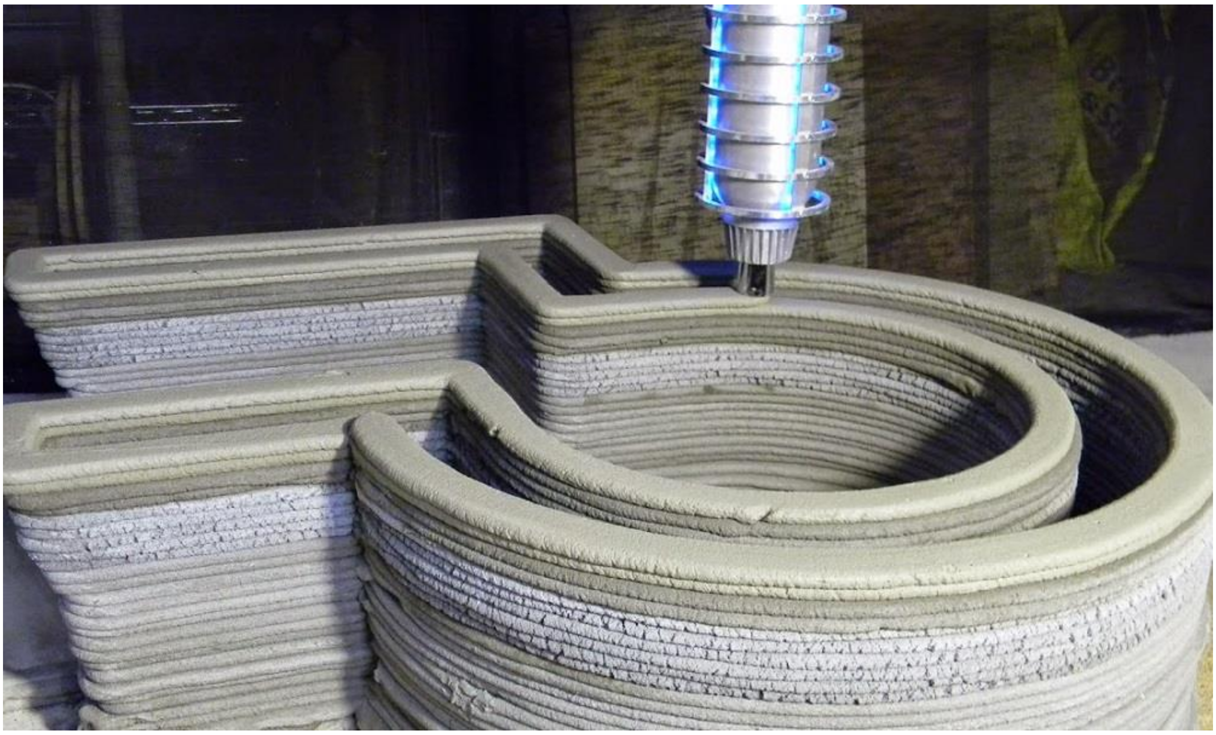


Figure 4: Concrete printer

3. ANALYSIS PHASE

The analysis phase of the report contains the main research steps covered by the following elements: market, competition, species, materials, process of 3D printing with concrete. Those researches provide many insights that can be important in the idea generation and the conception.

3.1 Market research

Historically, artificial reefs have been made of polluting materials such as plastic, concrete, or metal. Nowadays, however, there are options for using environmentally friendly materials and finding the best way to minimise waste. 3D printed artificial reefs are an innovative product even though there have been several projects with this technology. For instance, some projects can be quoted such as The Recif Lab project, Coral 3D and Living Sea Sculpture which takes place all around the world.

Using 3D printing technology make it possible to minimise the production time and the material consumption by 3 according to the paper Design Transactions: Rethinking Information Modelling for a New Material Age [3]. In every project the limitations are due to the manufacturing process and the size of the printer. To solve the issue most of them will create artificial reefs in multiple parts. They all use different materials such as ceramics, silica sands, concrete or even eco concrete but some research is still in progress to find better materials more sustainable and less polluting.

That said, the focus of our research is on some existing artificial reefs created for some other bigger project. [4], [5], [6]. Even so it is important to point out that every artificial reef is different by its shape, construction or size. It is very hard to find a consistency between all of them and that is why 3D reefs constructor do it personalise each one of them.

3D printed artificial reefs can be found almost everywhere from Australia to the United States through Europe. In the next table are designs for some of them with complementary information. The table gives information about four different reefs such as their price, the location, materials used and the project attached to it. Thanks to this table it will possible to give a first idea to the team about parameters and some inspiration of the design.

Figure 6: 3D printed artificial reef (1)

Figure 5: 3D printed artificial reef (2)

Figure 8: 3D printed artificial reef (3)

Figure 7: 3D printed artificial reef (4)

	Artificial reef 1	Artificial reef 2	Artificial reef 3	Artificial reef 4
Shape				
Location	Calanques (FR)	Sete (FR)	Maldives	Marine Park (Hong Kong)
Size	1,1x0,9 x 1,1 m	8 x 6 x 6,5 m	4 x 3 x 4	40m² x 60 cm
Weight (kg)	900	105 000	Unknown	Unknown
Modular part	1	1	220	128
Price	224 000€	600 000€	Unknown	Unknown
Materials	Sand based concrete	Special concrete	Ceramics filled with concrete	Terracotta clay
Project	Rexcor	Recif Lab	Modular Artificial Reef Structure	——

Table 1: Summary table of some artificial reefs

3.2 Competitive research

The creation of artificial reefs is due to several players such as governments, NGO or companies. They all have the same purpose: protect the environment by reinforcing the ecosystem.

For the project, the marine environment, 3D printing and immersion are the main focus to find information about artificial reefs. Although marine environments and immersion are important, the main subject is 3D printing.

The following companies are found specialised in the marine environment: Select in Vivo, Seaboost, Boskalis and Pro drive for immersion. 3D printing companies D-shape, XtreeE and Reef Design Lab are the main companies involved in the creation of artificial reefs. They all specialise in the conception of 3D printed concrete. D-shape is an Italian company born in 2007. They use silica sand with chemical binders to have as little waste as possible. They have created big structures such as bridges, buildings and restoration of sites. XtreeE is a French company born in 2015. With their technology they are able to create big structures with great precision to create innovative and sustainable projects. Reef design lab is an Australian company born in 2014. They use conception assisted by computers to adapt the specific needs of ecosystems. The materials are ecological concrete and coral sand. They only work to create new artificial reefs and restore the sea floor around the world with NGO and other partnerships.

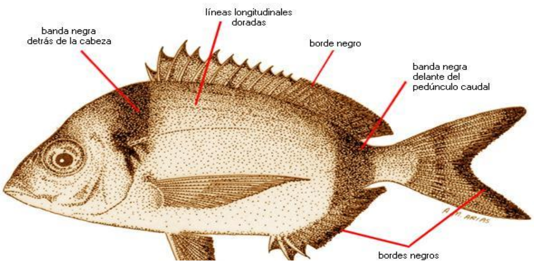
3.3 Analysis of different species [7]

The comprehensive study of the diverse species of fish inhabiting the target area provides valuable insights that directly inform the design and implementation of the artificial reef project. Moreover the objective of analysing the species, is also to determine the dimensions of the future design. Parts of it such as the central and the spaces between pieces, was determinated by this research. By examining the ecological requirements, behaviours, and specific habitat preferences of these fish species, a deeper understanding of the key factors necessary for the successful establishment and utilization of artificial reef structures has been gained.

The research highlights the importance of considering the natural feeding patterns, breeding habitats, and shelter requirements of various fish species when designing artificial reefs. By replicating these critical elements within the artificial reef structure, the project aims to attract and sustain a thriving ecosystem of fish, fostering biodiversity and enhancing overall ecological resilience.

Overall, this study emphasizes the critical role of understanding the local fish community in designing effective artificial reef structures. By considering the ecological requirements and habitat preferences of different fish species, the project aims to maximize the benefits of artificial reefs, creating sustainable habitat and promoting biodiversity. The integration of scientific research with the design and implementation of artificial reefs is crucial for the success and long-term viability of these valuable marine conservation tools.

To create the most suitable design for the area, an analysis about the species and biodiversity of the zone. The main species are the following ones: A variety of *Diplodus* specimens can be found



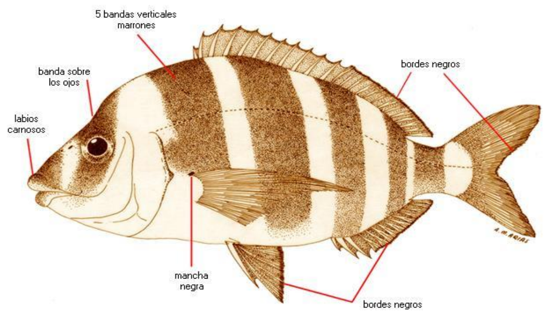


Figure 9: Diplodus

in the area, such as *Diplodus vulgaris, Diplodus saragus, Diplodus puntazzo, Diplodus cervinus* and *Diplodus annularis*. Usually they are diurnal, but you can also meet a few scattered individuals at night. Their common dimensions come from 45 cm to 60 cm.

This species is spindle-shaped and it has a more flattened head compared to *Diplodus annularis*. It has a characteristic roundish spot with a white border that distinguishes this species from *Diplodus annularis*. It can be observed in large shoals during the day, but also as scattered individuals. Furthermore, it can also be observed at night in scattered individuals. Their maximus length comes to 36.6 cm.

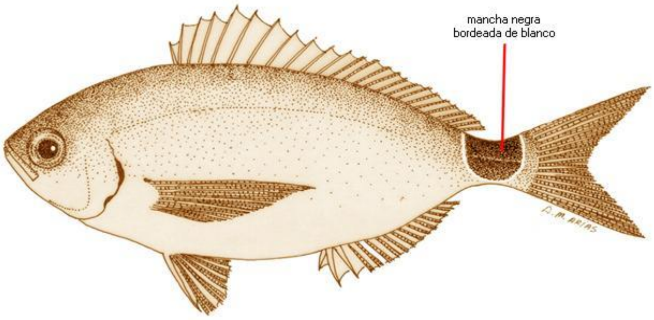


Figure 10: Oblada melanura

While swimming it can be observed that his mouth is slightly open showing his teeth. Diurnal/crepuscular species, it is distinguishable for its large size and the characteristic shape of the head. Their common length is 50.0 cm, but they can come up to 100 cm.

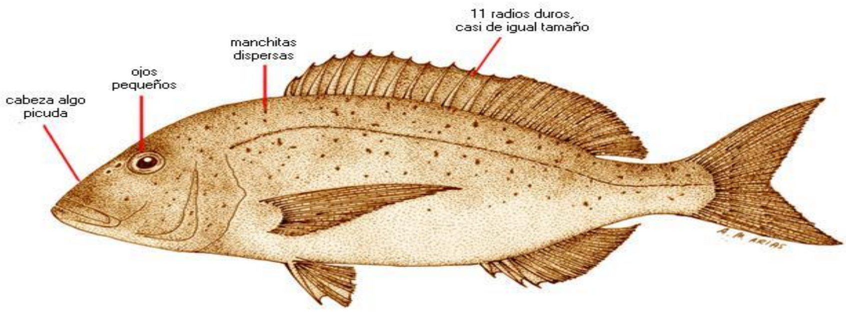


Figure 11: Dentex Dentex

It has a distinctive golden bump on the forehead and a large black rounded spot above the side fins. It has large “lips” and a black border on the caudal fin. This is also a large species like *D. dentex*. It is a very important diurnal species for fishing (therefore the same precautions made for *D. dentex* must be applied). Their common length is around 35 cm. However, their maximum length is 70 cm.

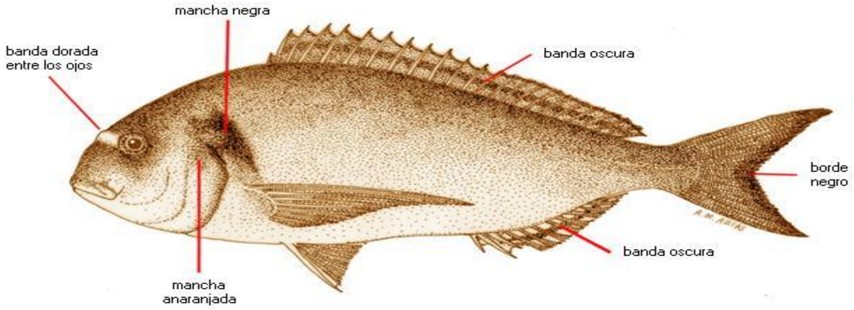


Figure 12: Sparus aurata

Large species, with yellow longitudinal lines and small black points above the lateral fins. It is often observed during the day in schools of many individuals. Their maximum length is 51.0 cm but they are usually around 30 cm.

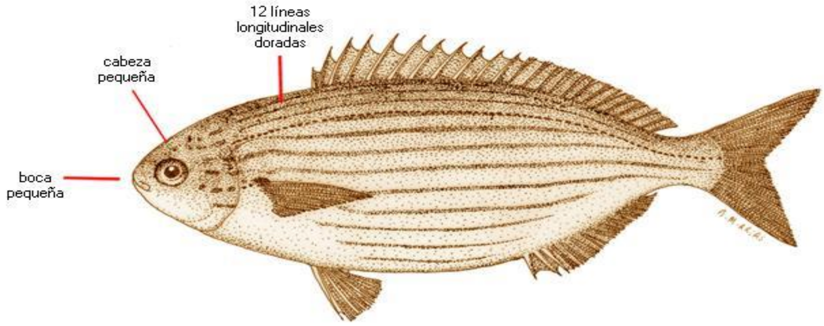


Figure 13: Sarpa salpa

It has a golden lateral line, a small black dot above the lateral fins and a continuous dorsal fin. This last characteristic distinguishes this species from *Atherina* sp. Indeed, it can be confused with *Atherina* sp. due to its fusiform shape and small size. In addition to distinguishing this species from *Atherina* sp. one can also use the shape of the mouth which is straight in this species, while it is oblique in *Atherina* sp. It is a diurnal species that can often be observed also during the night hours. Their common length is 20 cm, but they can come up to 40.0 cm.

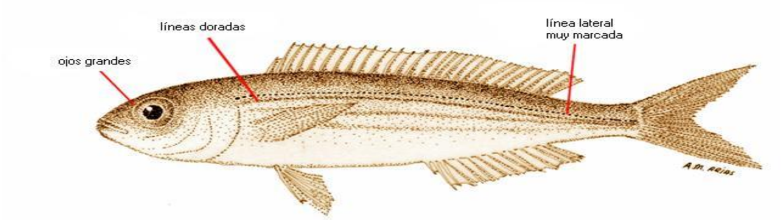


Figure 14: Boops boops

These are some of the biggest species that have been seen on the installations of OBSEA. [7]

2.3 Area: OBSEA Expandable Seafloor Observatory

In order to effectively execute the project, it is important to note that the chosen location for the implementation of the artificial reef should be situated in close proximity to the OBSEA seafloor observatory. This observatory, which has been installed a few kilometres off the coast of Vilanova I La Geltru by the company SARTI, is capable of continuously acquiring high-resolution data over extended periods of time. The observatory provides a range of important information and parameters, including but not limited to water temperature, current speed and direction, sound velocity in water, and water conductivity. These parameters are crucial for the successful execution of the project, as they will enable the hydrodynamic simulation to be carried out. Additionally, it is pertinent to note that the depth of the seafloor at this location is 19 meters and should be taken into account during the project's planning and execution. It will also be an advantage to have the reef near this observatory so an eye will be kept on it. [2]

Figure 15: Location and installations of OBSEA Expandable Seafloor Observatory.

3.4 Materials

The project brief specified the selection of 3D concrete printing as the production process. The focus was on examining the nature of concrete as a material and exploring potential ways to enhance its sustainability. Concrete is the most widely used building material in the world, thanks to its variety and durability. However, manufacturing cement, the binding material in concrete, is a highly energy and water-intensive process. The sheer volume produced, over 2 billion tons per year globally, is detrimental to the environment. The main ingredient in the most widely used concrete is Portland cement, which accounts for about 5% to 10% of all greenhouse gas emissions. Portland cement is made by heating limestone and other materials to extreme temperatures, causing greenhouse gases to be released into the atmosphere at a rate of one ton of carbon dioxide for every ton of cement produced.

To start at the beginning, what is concrete and what is it made of? Concrete is a mixture of cement, water, aggregates (such as sand, gravel, or crushed stone), and sometimes additional admixtures, which are added to alter the properties of the concrete.

In order to make concrete more sustainable, a study was performed on whether the various materials, which concrete is made of, could be replaced with a more sustainable option. Here looking at another option for water, since there is a global drinking water shortage and concrete is made from fresh water. It also looked at whether there are more sustainable options for cement and the aggregates that are added. Although for the most part the aggregates are already fairly circular.

3.4.1. Water

Sea water can be used for mixing concrete, but it is not recommended for most construction applications due to the high salt content. The salt in seawater can cause corrosion of the reinforcing steel in concrete, which can weaken the structure over time. However, there are some situations where sea water may be used for concrete production. For example, in coastal areas where freshwater is scarce or expensive, sea water may be used as a source of mixing water for concrete. In these cases, measures can be taken to minimise the potential for corrosion, such as using corrosion-resistant reinforcing steel or adding corrosion inhibitors to the mix.

In addition, there are some special applications where sea water may be used for concrete, such as in marine structures or offshore oil rigs. In these cases, the concrete mix is designed specifically to withstand the harsh marine environment and resist corrosion. Overall, while seawater can be used for concrete production, it is not recommended for most construction applications due to the potential for corrosion. Freshwater is typically the preferred choice for mixing concrete, as it does not contain high levels of salt that can cause corrosion.

Since metal structures are not used in artificial reefs, it is possible to apply this with salt water. There will be no corrosion and since there is plenty of seawater this is a more sustainable option.

3.4.2. Cement

Cement is a binding material that is used in construction to bind other materials together. It is the most widely used construction material in the world and is a key ingredient in the production of concrete, mortar, and other building materials. Cement is typically made by grinding together a mixture of limestone, clay, and other minerals, then heating the mixture in a kiln to a temperature of about 1,450°C. The high temperature causes the raw materials to chemically transform into a new material called clinker, which is then ground into a fine powder to produce cement.

Clinker is a key component in the production of cement, but it is also a major contributor to greenhouse gas emissions. As such, there is a growing interest in finding sustainable alternatives to clinker in cement production.

Here are some of the sustainable alternatives to clinker:

1. Fly ash: Fly ash is a byproduct of coal-fired power plants and can be used as a partial replacement for clinker in cement production. It is a cost-effective and widely available material that can help reduce the carbon footprint of cement production.
2. Ground granulated blast furnace slag (GGBFS): GGBFS is a byproduct of the iron and steel industry and can be used as a replacement for clinker in cement production. It is a highly sustainable material that can improve the durability and strength of concrete.
3. Calcined clay: Calcined clay is a highly sustainable alternative to clinker that is made by heating clay at a lower temperature than clinker. It has a lower carbon footprint than clinker and can provide similar properties to traditional cement.

4. Alkali-activated materials (AAMs): AAMs are a class of cementitious materials that are made by mixing industrial byproducts, such as fly ash or slag, with an alkali activator. They can provide similar strength and durability to traditional cement, but with a much lower carbon footprint.

Overall, these sustainable alternatives to clinker offer a promising path for reducing the environmental impact of cement production. By using these materials, the construction industry can create more sustainable and environmentally friendly building materials.

3.4.3. Aggregates

Since aggregates are mostly already natural materials, preserving this is not a necessity. However, consideration can be given to whether this can be made from more circular materials. Such as sea animal shells. If one orders seafood in the restaurant, in most cases the carcasses go into the trash. Something could possibly be done with this. [8]

Here are some examples of strong and durable aggregates that are commonly used in concrete:

1. Crushed stone: Crushed stone is a commonly used aggregate in concrete that is made by crushing large stones into smaller pieces. It is a durable and strong material that is capable of withstanding heavy loads and high traffic.
2. Gravel: Gravel is another common aggregate used in concrete that is made up of small rock fragments. It is a strong and durable material that is well-suited for use in concrete structures that will be exposed to heavy loads or harsh environmental conditions.
3. Recycled concrete: Recycled concrete is a sustainable aggregate option that is made by crushing and reusing old concrete. It is a strong and durable material that can help reduce waste and environmental impact.
4. Steel slag: Steel slag is a byproduct of steel manufacturing that is often used as an aggregate in concrete. It is a strong and durable material that can help reduce the environmental impact of concrete production by using a recycled material.

Seashells can be used as a sustainable alternative to traditional binders in concrete production. Seashells contain high levels of calcium carbonate, which can be used as a binding agent when ground into a fine powder. Here are some of the potential benefits of using seashells as a binder in concrete production:

- Reduced CO2 emissions: Seashells can be used as a substitute for traditional cement, which is a major source of CO2 emissions in the construction industry. The use of seashells can significantly reduce the carbon footprint of concrete production.
- Recycling of waste materials: Seashells are a waste material that is produced in large quantities by the seafood industry. By using seashells as a binder in concrete production, this waste material can be recycled and put to good use.
- Increased durability: Seashell-based concrete has been found to have higher compressive strength and better durability than traditional concrete. This can lead to longer-lasting structures and reduced maintenance costs.
- Improved aesthetics: Seashell-based concrete can have a unique and attractive appearance, making it a desirable option for architectural applications.

However, there are also some challenges associated with using seashells as a binder in concrete production. For example, the supply of seashells may be limited in certain regions, and the process of grinding seashells into a fine powder can be energy-intensive.

3.4.4. Sustainable concretes

There is also so-called sustainable concrete. Sustainable concrete refers to concrete that has been designed and manufactured with the goal of reducing its negative impact on the environment and improving its long-term sustainability. [9]

There are several different types of sustainable concrete, including:

- Recycled concrete: This type of concrete is made from crushed and recycled concrete, which reduces the amount of waste in landfills and reduces the need for virgin materials.
- High-performance concrete: This type of concrete is designed to be stronger and more durable than traditional concrete, which can reduce the need for frequent repairs and replacements.
- Low-carbon concrete: This type of concrete is made using alternative materials such as fly ash, slag, or silica fume, which can significantly reduce the amount of CO2 emitted during the production process.
- Self-healing concrete: This type of concrete contains capsules of healing agents that can be activated when cracks appear, allowing the concrete to repair itself.
- Previous concrete: This type of concrete allows water to pass through it, which can help to reduce stormwater runoff and the risk of flooding.

Overall, sustainable concrete is an important innovation in the construction industry as it allows for the creation of buildings and infrastructure that are more environmentally friendly and sustainable.

Figure 16: Concrete printed AR as sustainable solution

3.5 3D printing with concrete

As a part of the EPS artificial reefs project, a concrete 3D printer will be used to fabricate innovative structures. The concrete 3D printer is a revolutionary technology that allows for the creation of objects using concrete as the base material. It works by depositing successive layers of liquid concrete, which hardens to form a solid and durable structure. This technology offers numerous advantages, such as the ability to create complex and customized shapes, reducing waste and production costs, as well as decreasing dependence on labour. By utilizing this concrete 3D printer, it is able to design artificial reefs that provide a suitable habitat for marine life, thereby contributing to the preservation and restoration of marine ecosystems.

The 3D concrete printer employed in the production of the artificial reef represents a university-owned apparatus situated at the Terrassa Campus. A comprehensive on-site assessment was conducted to investigate the pertinent constraints entailed in utilizing this printer for artificial reef fabrication. The findings revealed that while the printer exhibits commendable capabilities in constructing intricate geometries, several limitations warrant consideration to ensure optimal performance and desired outcomes.

Figure 17: Pictures of the 3D printer in Terrassa

One notable constraint of the 3D concrete printer is the diameter of the nozzle, which measures 3 cm. Consequently, the thickness of the produced objects must align with multiples of 3 cm to ensure accurate deposition of the concrete material. Additionally, the printer allows for a maximum height of 30 cm, limiting the vertical extent of the printed structures. These constraints must be taken into careful consideration during the design and planning phase to ensure compatibility with the capabilities of the 3D concrete printer and to optimize the successful fabrication of the desired objects.

In concrete 3D printing, the vertical orientation of the nozzle and the time required for concrete to dry present limitations in creating horizontal-axis lateral holes. The gravity-dependent nature of concrete makes it impossible to print in mid-air without adequate support. Hence, the deposition of the extruded material onto existing layers is necessary to prevent the concrete from falling due to its own weight.

During the concrete 3D printing process, layers are deposited successively, and each layer requires a solid foundation to maintain its shape during the curing phase. Consequently, when attempting to incorporate horizontal-axis holes or cavities, they must be oriented vertically to allow the material to be deposited onto an existing surface instead of being suspended in mid-air. This constraint restricts the feasibility of creating horizontal holes within concrete printed objects, as there is no underlying material support beneath the suspended portions.

Therefore, due to the structural support requirements and the necessary drying time for concrete, traditional concrete 3D printers are unable to produce lateral holes with a horizontal axis. This limitation restricts design possibilities; however, vertical holes can still be created, and alternative structural designs can be implemented to accommodate specific project requirements.

4. PROGRAMME OF REQUIREMENTS

4.1 Short list of requirements

The short list of requirements that contain the most important requirements are for the design:

1	Has to be concrete printed.
2	Has to be a modular.
3	Adaptable to environment.
4	Has to be 1 meter diameter.
5	Safe for the environment.

4.2 List of requirements

nr	Requirement
	Presentation
1.1	The lifetime of the reef has to be as long as possible.
1.2	The pieces have to be able to gather.
1.3	The design has to be outstanding.
	Dimensions
2.1	The entire design of an artificial reef won't exceed a diameter of one meter.
2.2	One piece must have a high of 30cm maximum.
2.3	One piece must be able to be lifted by a human.
	Material
4.1	The material of the artificial reef is concrete.
4.2	The material mustn't be affected by the sea water.
4.3	The material that comes into contact with water must not be able to rust.
4.4	The material won't break under the pressure of the water.
4.5	The material shouldn't be able to move due to the velocity of the water.
4.6	The pH's material has to be close to 8.3.
	Safety
5.1	The reef shouldn't be harmful for the fauna and flora.
5.2	The reef shouldn't be harmful for the sea water.

	Distribution
6.1	The pieces must be transportable by any vehicle.
	Production
9.1	The design has to be concrete printed.
9.2	The design's production should be as easy as possible.
9.3	The components' production have to be sustainable as much as possible.
9.4	The design's production should leave as little as possible of waste.
	Design
10.1	The product has to be in modular parts.
10.2	The design must be adaptable to the environment.
10.3	The holes will be created to allow fishes to live.
10.4	The holes will be created to let the current get through the reef.
	Ergonomics
11.1	The different pieces should be easy to assemble.
11.2	The different pieces will be easily transportable.
	Environment
12.1	The reef will stand on the sand.
12.2	The reef is located in a protected environment.
	Mechanical
13.1	The product must be able to be constructed (from stored position) in less than 30 minutes.

5. DESIGN PHASE

Based on the design question and context, in conjunction with a first version of the Program of Requirements, the idea phase is started. In the idea phase, a broad search is performed for design solutions that fit the described design question. In general, the boundaries of the design space will be explored. These solutions are then subjected to a variety of investigations.

5.1 Method (plan of approach)

The aim of this project is to create an innovative idea for the design of artificial reefs. To do so the first ideas and prototypes are being based on the article and scientific research *Proposed Conceptual Framework to Design Artificial Reefs Based on Particular Ecosystem Ecology Traits done by Luis Carral, María Isabel Lamas, Juan José Cartelle Barros, Iván López, Rodrigo Carballo* [5].

Thanks to their previous work, it has been possible to obtain a methodology to create the most efficient and suitable design.

Their work proposes an analysis for the creation of artificial reefs. The analysis of different partial indices is discussed in the article. In the next steps of the project, the 3D prototypes will be examined to create the most suitable design for the proposed area. This process enables the comparison of different models to determine the one that best fits the requirements.

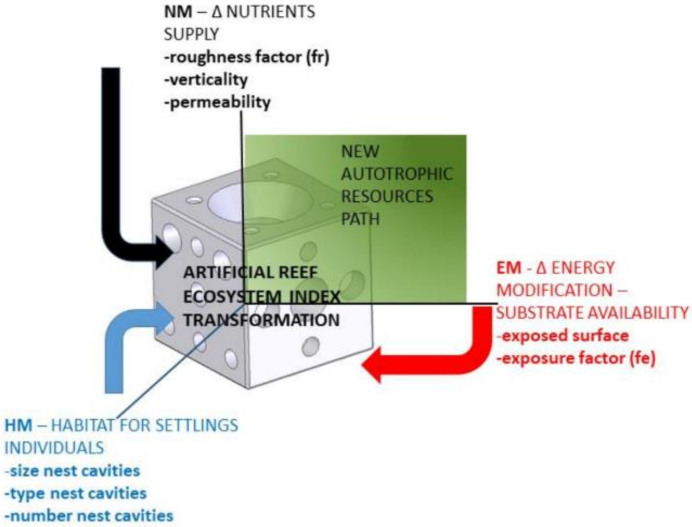


Figure 18: Graphical representation proposal for the AREIT partial indices: EM (energy modification), NM (nutrient modification) and HM (habitat modification) including the most important factors that affect each one of the indices

The first observation made is the requirement of an open hole to enhance the flow of currency inside the artificial reefs, thus creating a nutrient supply. Additionally, the analysis of surface and roughness factors will play a crucial role in facilitating the development of microorganisms and other species on the model's surface.

Furthermore, the creation of small holes becomes necessary to provide protective spaces for smaller species. This enables the establishment of hiding places for ecosystems, safeguarding them from predators and other potential harm.

The primary objective is to establish a modular structure. This approach offers not only an adaptable design but also extends the lifespan of the product by simplifying maintenance. This aspect holds great significance for the project, as the overarching goal is to provide a sustainable, long-lasting solution that minimizes waste and contamination.

Moreover, the implementation of a modular design opens up possibilities for utilization in other areas by modifying the structures and modules.

5.2 Idea generation

In the initial sketches, the objective was to explore a method for connecting the various parts of the design with their distinct geometries. The accompanying figures illustrate one of the early concepts, wherein the structure enables the pieces to be securely fastened. This approach holds significant promise as it allows for manual construction without the requirement of permanent fixation.

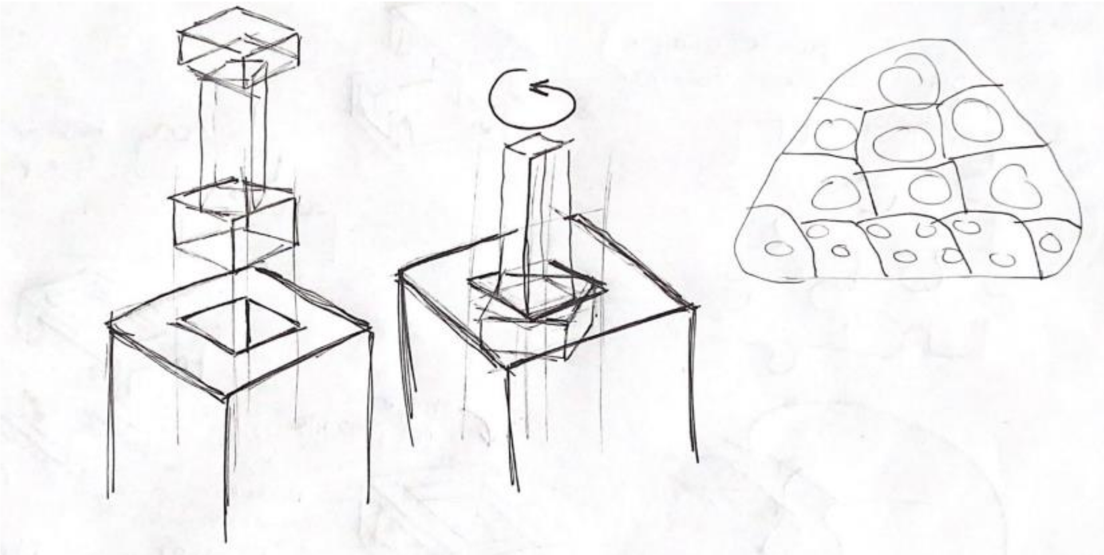


Figure 19: First sketches by hand. Idea of connecting pieces by using their own geometry

To continue, an analysis of various modular structures and geometries was conducted. The exploration began with the consideration of the puzzle concept and its potential application to the design. However, some initial ideas had to be discarded due to limitations posed by the 3D printing methodology and its associated possibilities.

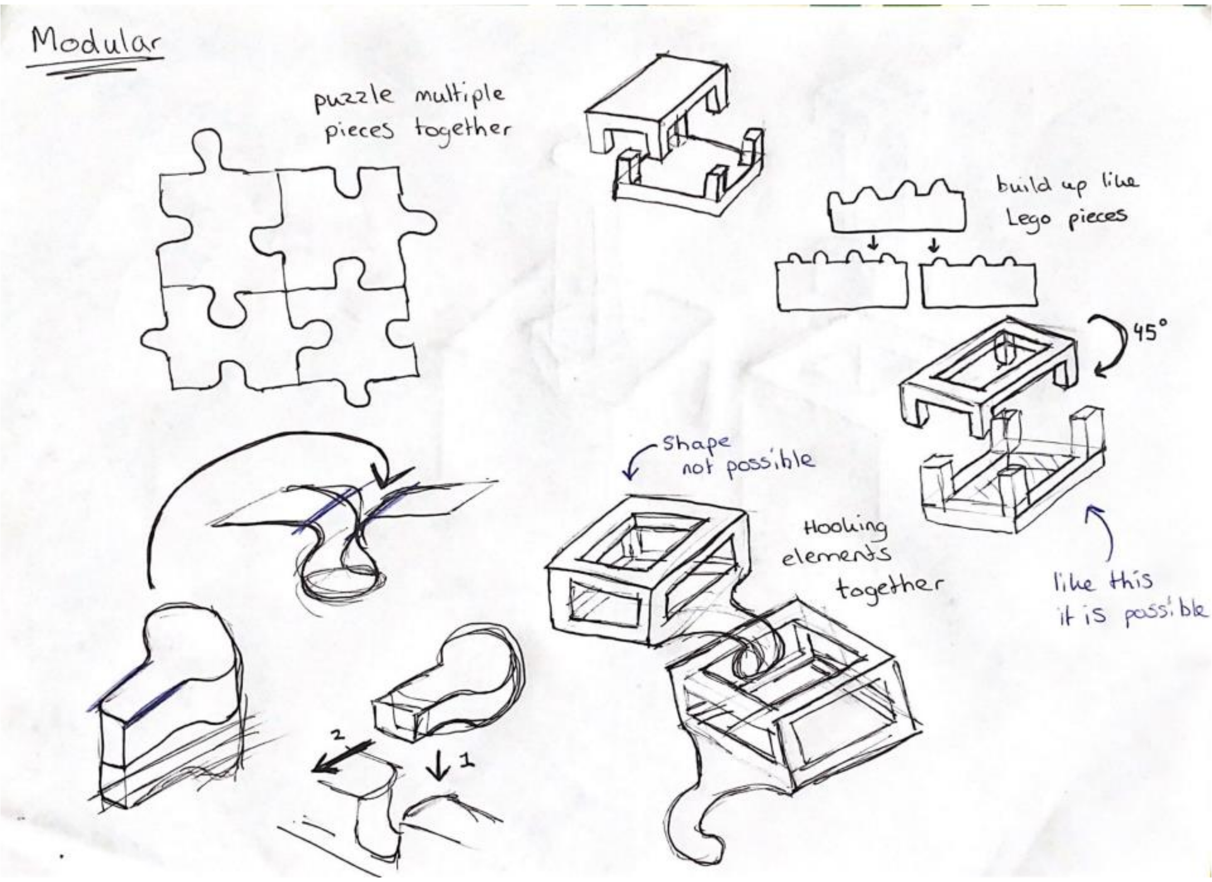


Figure 20: Initial sketches and concepts for different modular structures

As can be seen on the figure below, the idea of creating a design made by organic geometries was one of the first resources.

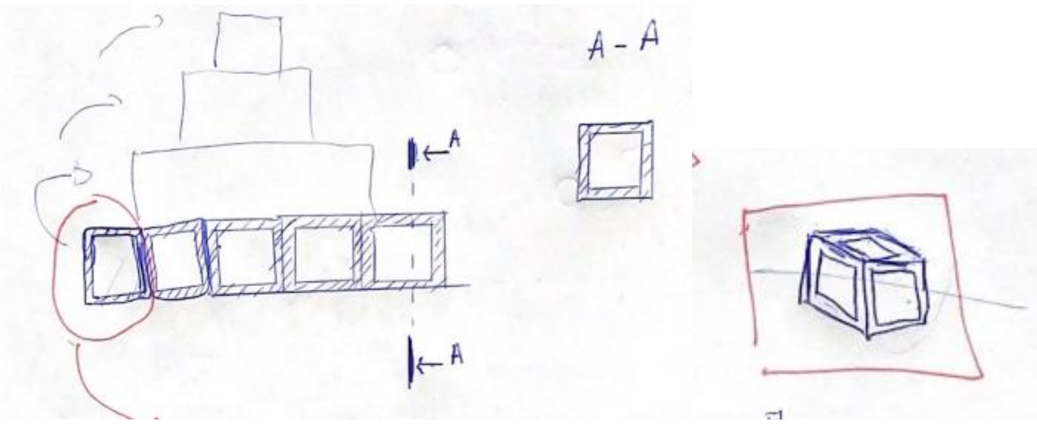


Figure 21: Sketches for different modular structures using basic geometries

It was important to create a design that could withstand the currents and other forces of the seabed with its own weight without the need to be tied to the seafloor. Achieving this would make it possible to implement the artificial reef without damaging the seabed. The following idea has been discarded because it uses moorings at its bottom to maintain stability.

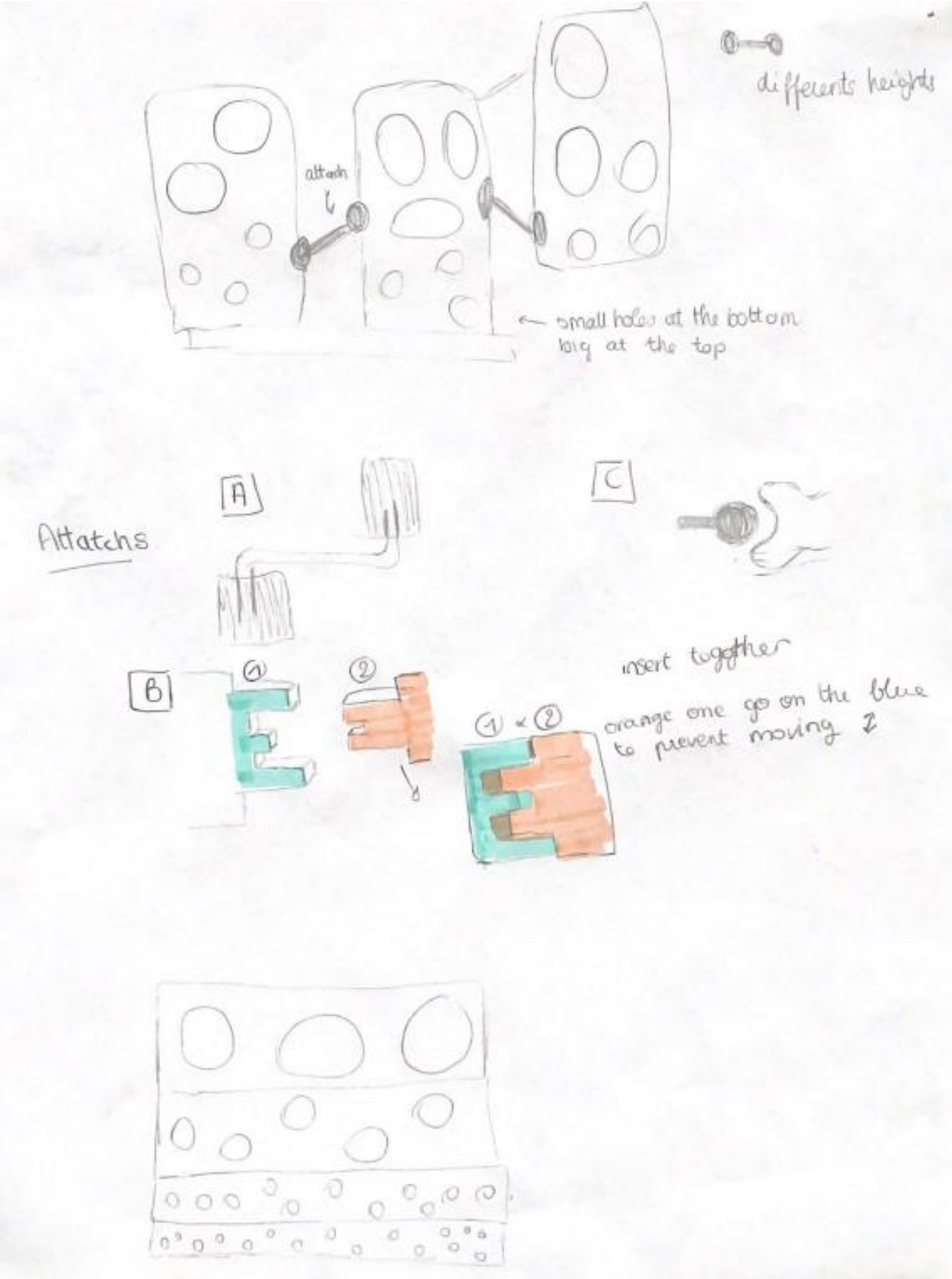


Figure 22: Initial sketches and concepts for different modular structures.

Continuing with the idea of creating a design using basic geometric shapes, it was decided to draw inspiration from other artificial reefs on the market, but by creating a structure based on two geometries: spheres and cylinders. These could be interconnected to provide the user with the ability to construct a customised reef, creating an almost universal model. Another advantage of this type of design is its maintenance, as its simple structure allows its parts to be easily replaced, thereby extending its lifespan. In addition, because of its spaces between the structure, it would create a lot of currency for nutrient supplement and also protection for smaller species by the creation of smaller holes on the spheres. Moreover, as this could create a square base, that could help in order to stabilise the structure without fixation by having a centre of gravity more centred than other designs.

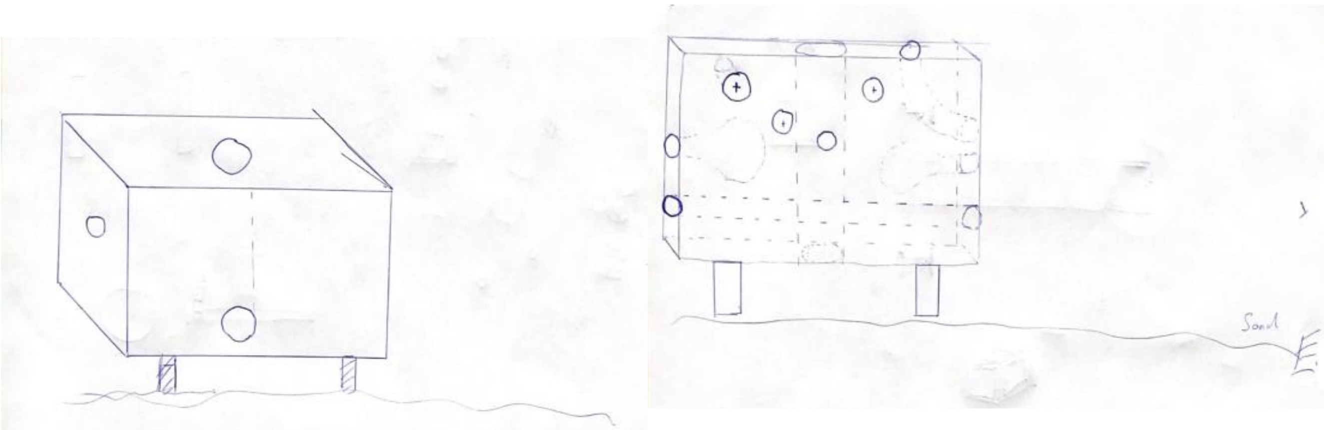


Figure 23: Initial sketches and concepts for different modular structures using basic geometry

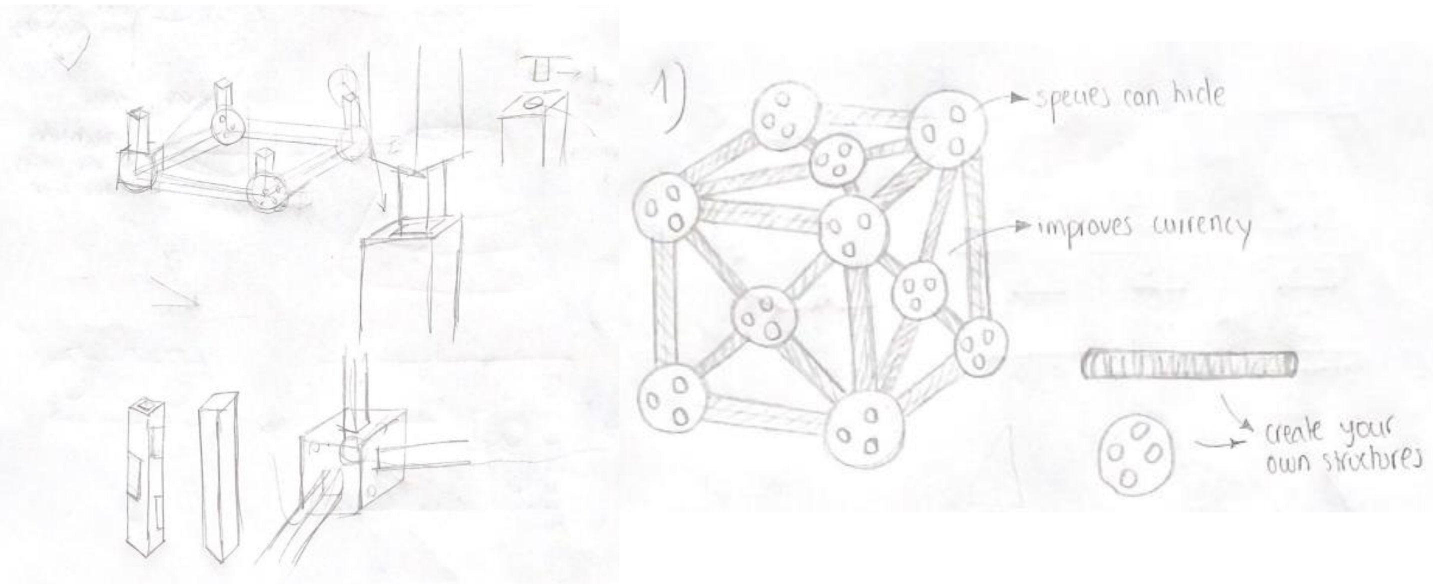


Figure 24: Sketches for different modular structure, by spheres and cylinders

Moving forward, the latest suggestion at that moment was to create a pyramidal structure with various holes of different sizes, as well as a central hole that would enhance water flow to meet the previously analysed requirements. It would be interesting to create different exchangeable modules with different sized holes so it can be modified during its presence on the seafloor.

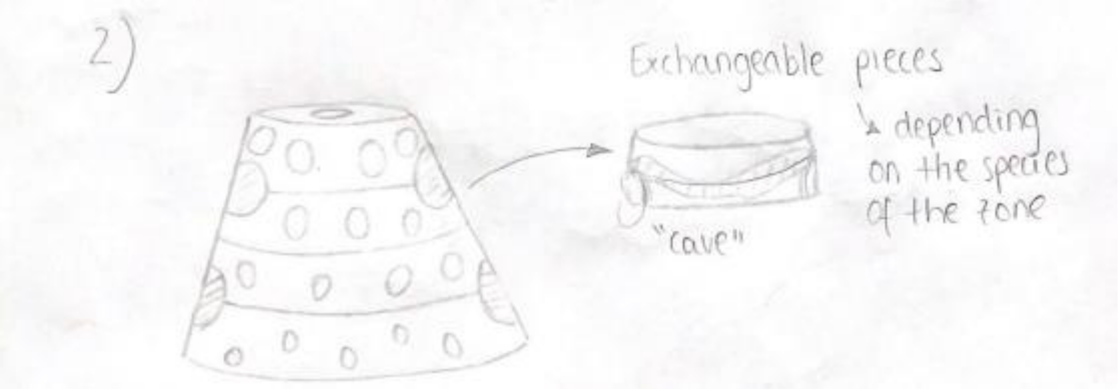


Figure 25: Artificial reef with a Pyramidal geometry

However, the next step is to analyse the structures in order to come up with the most suitable design.

6. CONCEPT PHASE

In the concept phase the concept are being brought on to the paper. This is the moment where all the individual solutions become one visible product. The concepts have been visualized by sketching with fine liner on A3-paper. Every concept contains a 3D perspective look at the total product. The functions and details of certain parts have been sketched in such a way that it looks zoomed in or more dynamic (Arrows, hands etc). Finally, the concepts have been given a name and a graphic style has been added.

6.1 Concept development

6.1.1 Atomic reef concept

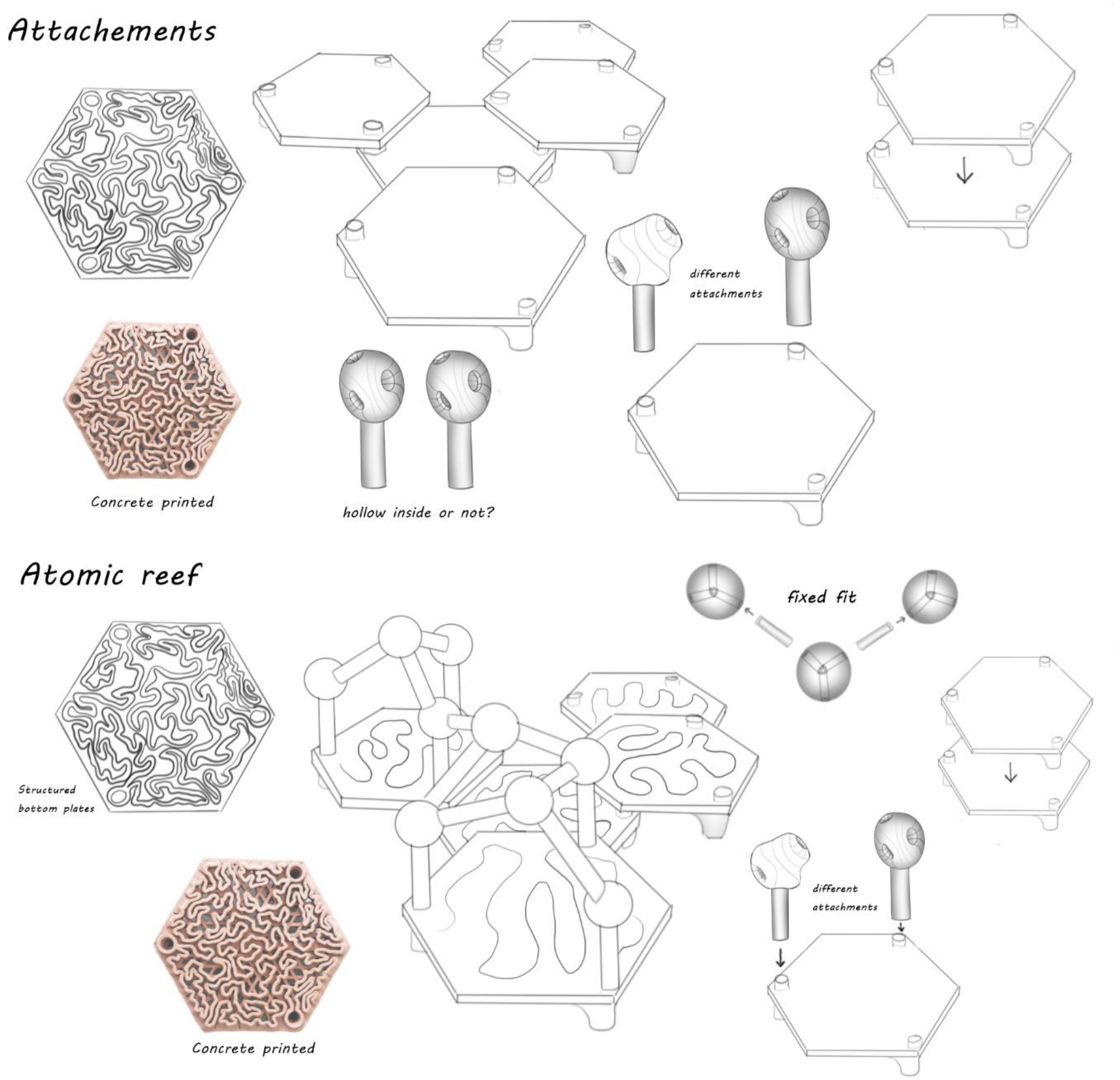


Figure 27: concept sketch atomic reefs

6.1.2 Pyramid reef concept

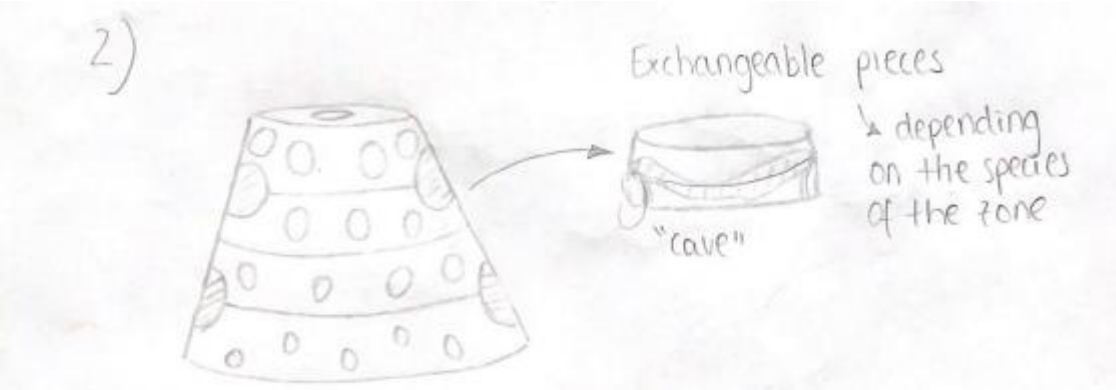


Figure 28: Pyramid reef idea sketch

The idea is already there but in the period that comes after the midterm this will be further developed into a full concept. On the bottom of the page there is a fuller sketch of this concept.

6.1.3 Click in table reef

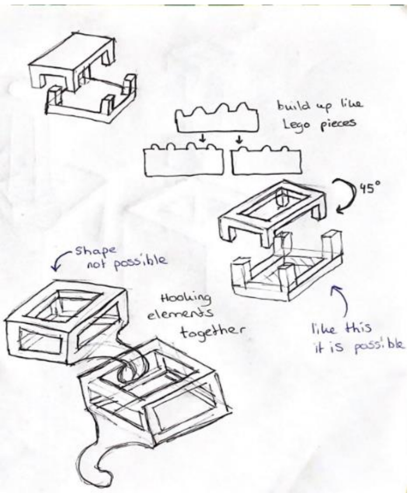


Figure 29: Click in table reef concept

This idea will also be worked on further as it does have potential if looked at further.

The shape is simple which makes it easy to make with low production costs since it can be made in a batch with several products.

After the midterm this idea will be further developed.

There will also be further exploration of multiple possibilities of shapes and concepts.

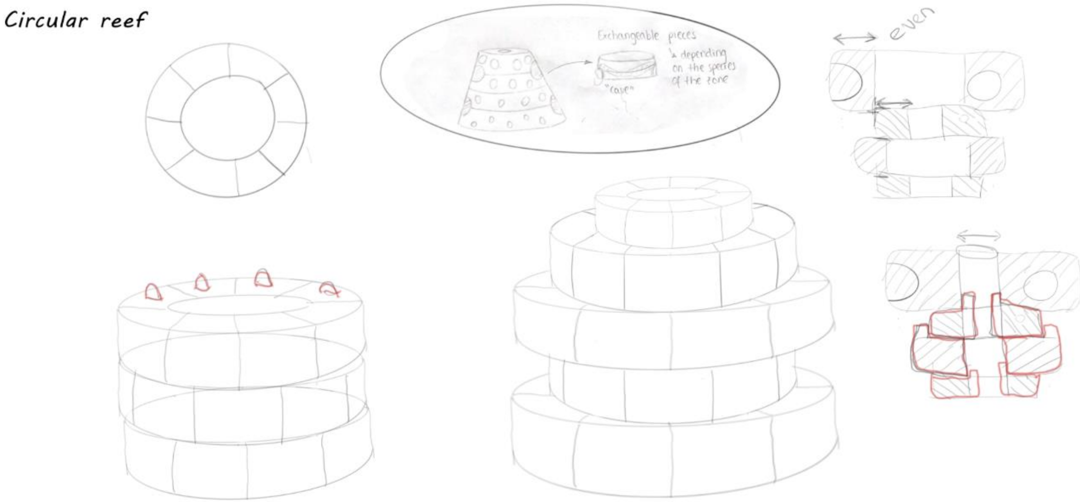


Figure 30: Circular reef concept

6.2 Final concept

After analysing the multiple ideas, it was decided to move forward with the circular reef concept. This decision was made because of the stability and the variety of options that this structure provided. By this choice, it was possible to come up with new concepts related with the circular reef concept. As it was stated before, different requirements where necessary to provide an optimal design for the species and location of the artificial reef: one of them being the need of creating a structure that was hallow inside. In addition, for the purpose of achieving a modular structure, it was decided that the circular structure will be made up by multiple pieces with the same design. This approach facilitates an intuitive design and simplifies the construction process underwater.

The first and most difficult decision that needed to be done was coming up with a way on how the pieces were going to be connected with each other. During the design face, this was vital because of the importance of the design resisting the water currency and other environmental situations. Moreover, as the project aimed to create facilitate the installation of artificial reefs by creating a design that can be easily transported and assembled, allowing it to be used by different public without the need for a significant financial investment for its assembly. As a result, the creation of easy connections was necessary. Throughout this project, this requirement will be analysed and developed.

Another important point was the weight of the design. In case the design needed to be heavier in a future, the idea of a "lid" was considered. This would contribute on incrementing the weight of the design in case its necessary to avoid the rollover of it.

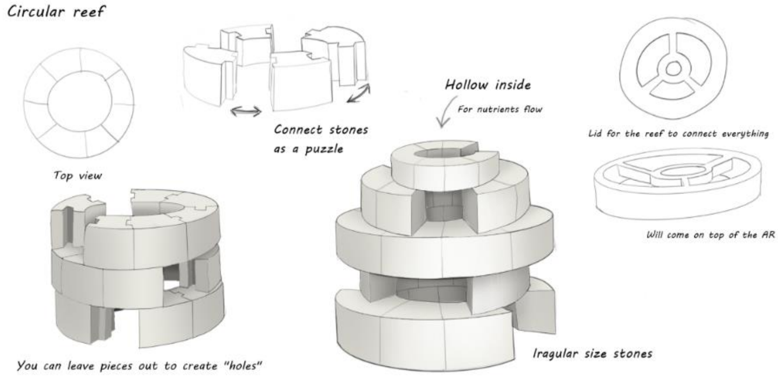


Figure 32: Design sketch original concept

6.3 Concept conclusion

The next steps will be to create a 3D prototype with conception assisted by computer and to define all the characteristics of the reef that will be created. By that it means the size, material, weight and resistance. The work will be done by doing simulation on the computer to ensure that the artificial reef created won't break with the currency or the pressure. One of the big tasks will be to evaluate different things about the artificial reef such as the efficiency of it, the costs of production and installation, the methodology of production and installation and the impact on the environment.

7. DESIGN STUDIES

With the design studies, the aim is to see if inside-out and outside-in studies can be made. What is meant by an inside-out study is looking at the placement of any electrical components of the design, since in an artificial reef there are no (electrical) components in the design, so this has been dropped. An outside-in study looks at the outside shape of the design. This involves a closer look at the possibilities of shapes and whether this is possible to produce with the production process.

Since the design will be a 12-sided dodecagon, a calculation was first made of how long the sides will be so that this becomes an even number without too many decimals. A dodecagon consists of 12 sides where the angles are in 150 degrees to each other. In figure 33 you can clearly see which basic shape was assumed.

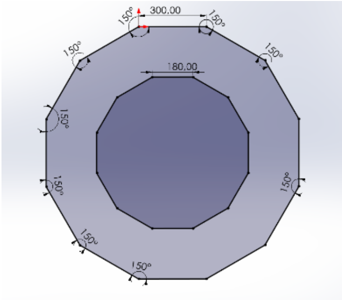


Figure 33: measurements dodecagon

7.1 Outside in

The outside-in study looked at various forms. It was quickly concluded that the original rounded shape was not possible with the production process: concrete 3D printing.

The figure below shows the original concept sketch. After analysing the production process, it has become clear that this shape is not possible to print. This chapter clearly explains why this is not possible and how this was solved.

From the design above, it can be seen that originally a part would look like this, see figure 34. Here, only how the different pieces that come on top of each other are going to be attached to each other has not yet been considered. Since not as much is possible with concrete printing as with plastic 3D printing, this had to be carefully considered so that the shape is possible in combination with the process.

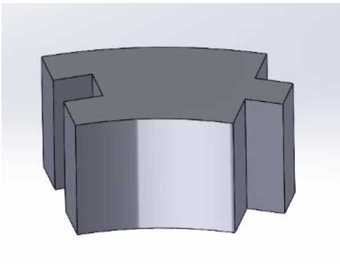


Figure 34: Part of circular reef

To give an example of how with this design it could be solved in terms of stacking the different elements, an image of it is shown below. Is this particular shape possible for printing only? The answer to that is; no. This is because the printer cannot make hollow spaces at the bottom, the bottom of the print must always be flat, there is an exception for this if support material can be placed, but the printer available for this project is not yet that advanced.

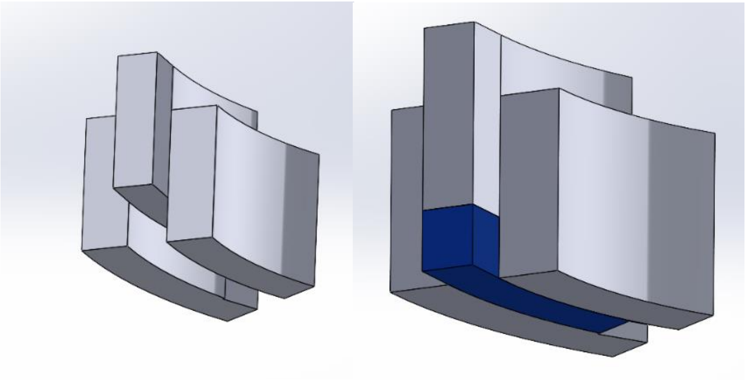


Figure 35: Improved part circular reef and why it's not possible

Figure 35 shows that if you wanted to print the design, the hollow space which is marked blue is not possible to create because the printer simply cannot produce it. Because the sides of the design are rounded off, this also reduces the freedom of design.

Even with the design shown here (printing the other way round as the design above), it is not possible to print this because otherwise material in the air has to be printed once.

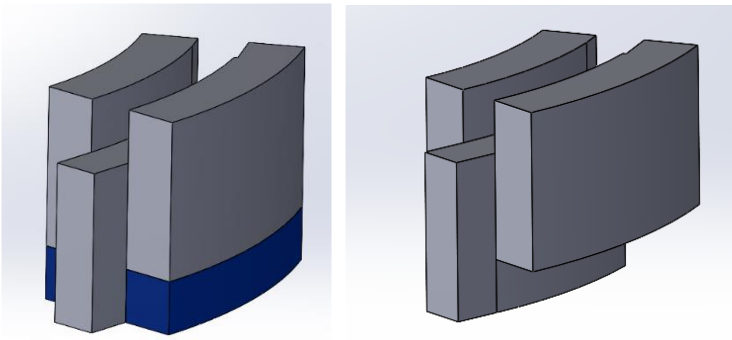


Figure 36: Improved part circular reef (2) and why this is also not possible

Therefore, the decision was made to move away from round edges and think about grabbing a hexagon, octagon or larger as a shape. The more corners there are in the design, the more components you can make which also means that a piece does not have to be super heavy and this can be installed more easily. More angles also have an advantage over the round shape. A dodecagon has an illusion of a circle because the angle becomes increasingly blunter.

7.2 Design studies conclusions

From the design phase, 3 designs were concluded, see figure 35, 36 and 37. A 3D scale model of these will be made of plastic. After a physical 3D model has been made, it is re-evaluated whether adjustments to the design are needed. Once this is all done, calculations and simulations are performed on these designs. On this basis, it is decided which design has the strongest construction. A prototype is then printed with the concrete printer. There is more detail on this in chapters 9 and 10.

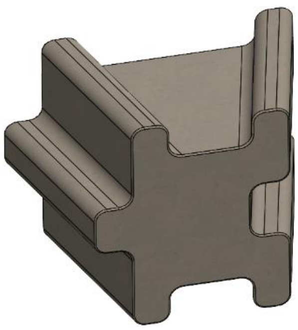


Figure 37: Design 1

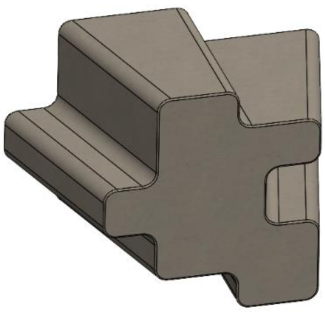


Figure 35: Design 2

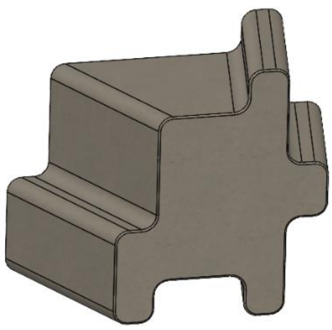


Figure 36: Design 3

8. 3D MODEL WITH TESTS

8.1 Plastic 3D printing characteristics

In order to ensure the successful assembly of various ring designs, preliminary tests were conducted by creating prototypes using Solidworks software. To facilitate the comprehension of the designs, it was decided to initially print scaled-down versions using a 3D plastic printer. This approach allowed for better visualization of the designs, enabling the assessment of measurements and identification of any necessary adjustments. The specific 3D printer employed for this purpose was the Sigma model provided by the University of Vilanova I la Getru, utilizing polylactic acid (PLA) as plastic material.

To familiarize ourselves with the printer's operation, Oscar Perez, a technician at the university's tech lab, provided detailed instructions. The printing process involved feeding a PLA wire into a tube, which then passed through an extruder. While the nozzle's diameter could be modified, the regular parameters, a 0.4mm nozzle diameter, and a 3mm PLA wire diameter, were maintained. The extruder was heated to 200°C, while the print bed was heated to 60°C. To optimize printing time, two printers were utilized: the Sigma and the Sigmax, the latter capable of printing two pieces simultaneously.

After conducting the initial print, it was observed that the two Lego pieces (Design 2: ie Figure 35) were unable to fit together due to a too thin space between the two pieces, necessitating modifications to the prototype in Solidworks before initiating a subsequent print. Furthermore, upon closer examination, it was noted that the puzzle's three corners (Design 3: ie Figure 36) appeared satisfactory, but the pieces exhibited less structural integrity when assembled together.

8.2 3D plastic scale model 1:10

In order to visualize and be able to have a better analysis of the designs, it was decided to develop a prototype. A 3D plastic scale model at a 1:10 scale was created by using a 3D printer. To compare the different models, it was decided to print different pieces of each of the three designs.

This was vital to analyse the connection between pieces and the stability of each structure as well. This was done by reducing the previous 3D model created on SolidWorks to the scale mentioned before. The final measurements and dimensions used for the plastic 3D printing can be found in the *Annexes*.

8.1.1. Model 1 (“Puzzle”)

This first model is one of the first ideas that was developed during the 3D modelling. Indeed, when putting the pieces together, this design felt one of the most stables. As a result, the following structure can be obtained.

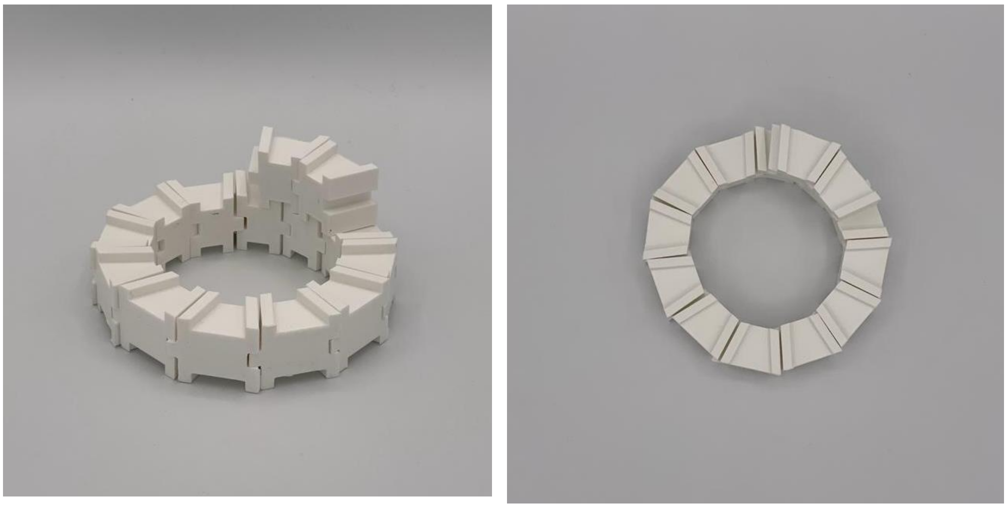


Figure 38: Assembly of the first model "Puzzle" with plastic 3D printed pieces

In the figure 38, the geometry of the pieces can be observed.

Figure 39: Plastic 3D printed pieces of the model 1 “Puzzle”

8.1.2. Second model ("Lego”)

The second printing was a completely different structure. However, the stability and easy construction of it made this model interesting. Moreover, because of the non-symmetrical shape of it, a strong connection between the pieces was achieved.

Figure 40: Plastic 3D printed pieces of the model 2 “Lego”

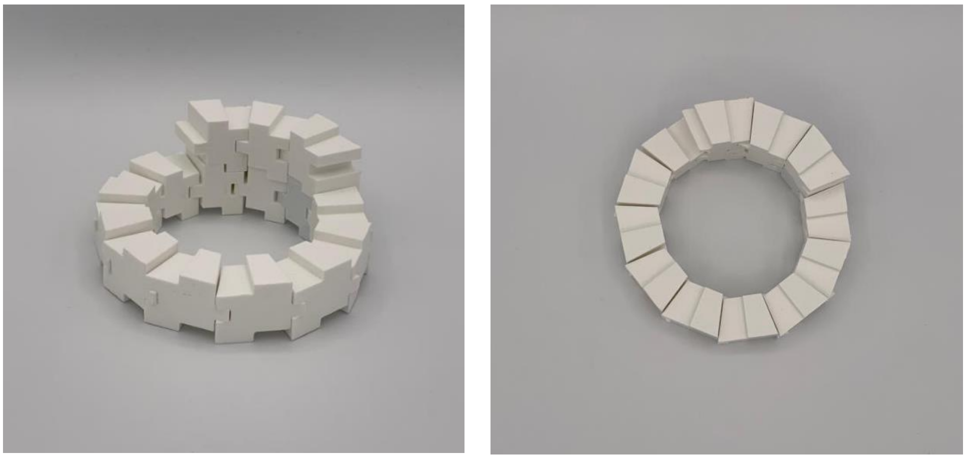


Figure 41: Assembly of the second model "Lego" with plastic 3D printed pieces

8.1.3. Model 3 ("Asymmetrical")

The next model was created by making a modification of the previous design. By doing so, the idea was to analyse if this structure could create little holes in order to improve currency in the structure.

When the pieces were put together, it could be appreciated that the structure was not as stable as the previous made. The pieces were standing by their own weight, what is not that appropriate for the efficiency of the design, since the model needed to bear the currents and other environmental conditions that can be found under sea.

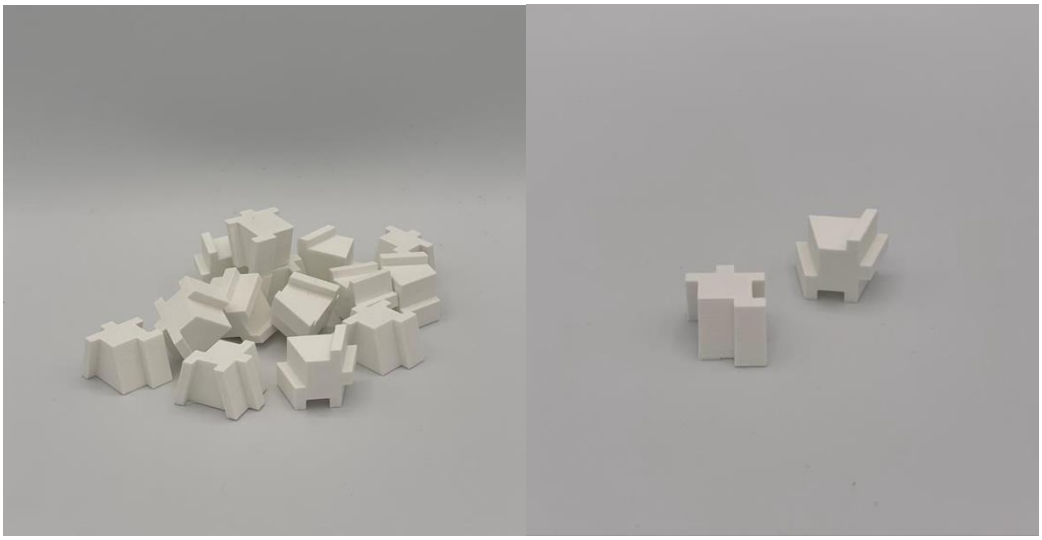


Figure 42: Plastic 3D printed pieces of the model 3 "Asymmetrical"

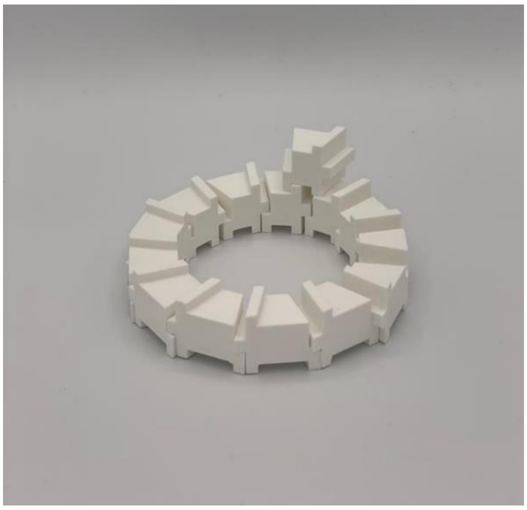


Figure 43: Assembly of the third model "Asymmetrical" with plastic 3D printed pieces

8.3 Tests conclusion

As a conclusion, after printing the different designs on a reduced scale it was possible to analyse the different structures and geometries of each of the models. By printing them the possibility of having problems with the connection between each of the pieces became a real issue, so it was decided it to begin with reduced number of printings with the concrete printer in order to visualize how the tolerance and roughness worked with that type of printer.

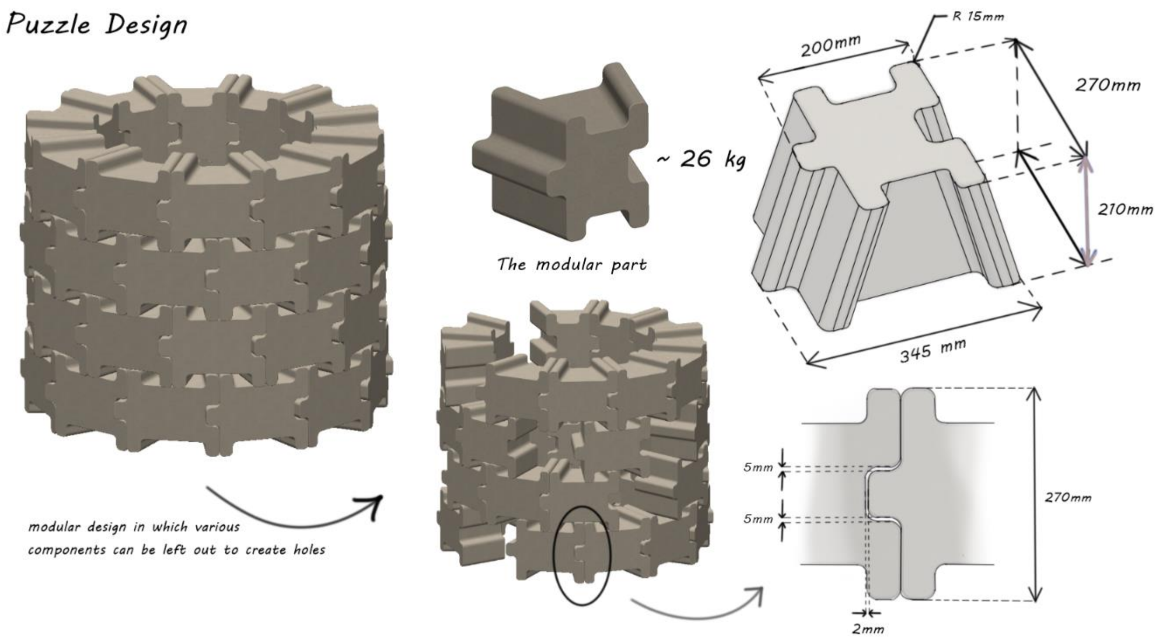
Moreover, the stability of the different designs was tested in a reduced scale. It is worth mentioning that by doing this first testing, it was also possible to test the ease of assembling the model. This is of great importance for the project, as it aims to create a design that can be easily transported and assembled, allowing it to be used by different groups without the need for a significant financial investment for its assembly. For this reason, the components must be capable of being assembled with relative ease, taking into account the conditions of the seabed and the reduced mobility of humans in this environment.

As a conclusion, it was decided to eliminate Model 3 as the stability of the structure was not as positive as the one the other two designs possessed. For that reason, this model will not be used during the simulations.

9. PRESENTATION DRAWINGS

From the prototyping, a new product was formed, A presentation drawing was made for this with the important aspects for each design.

9.1 Puzzle design

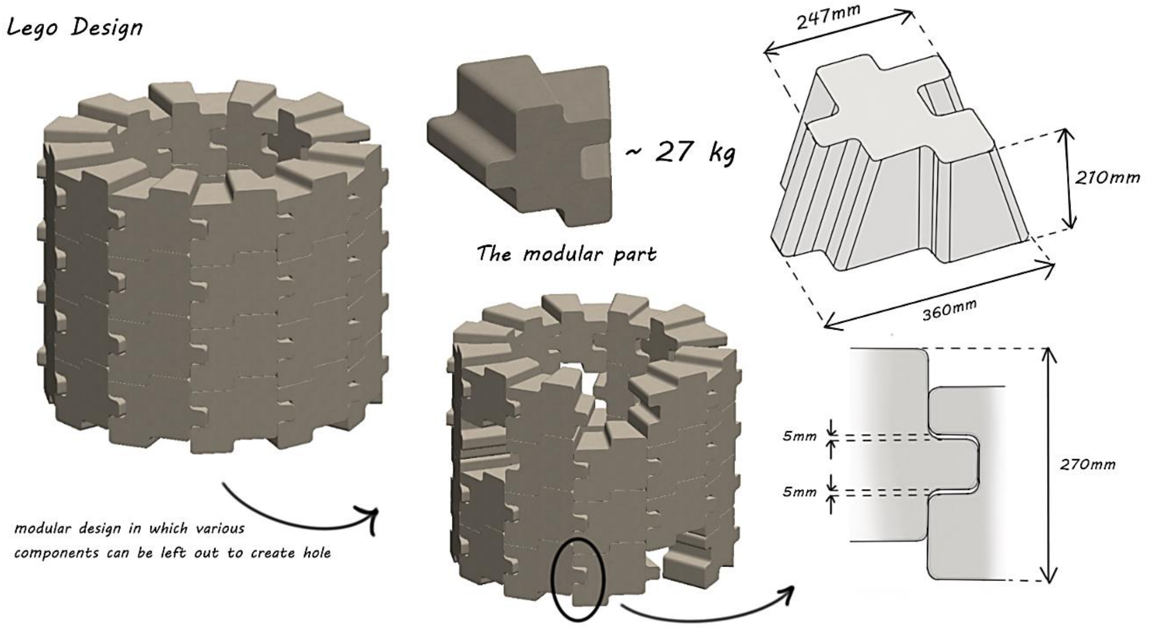


The overall design has an outer diameter of 1158 mm, its inner diameter is 718 mm. A part of the design has dimensions of approximately: 270x345x270 mm and weighs 26 kg.

This applies to the Puzzle, Lego and Asymmetrical design:

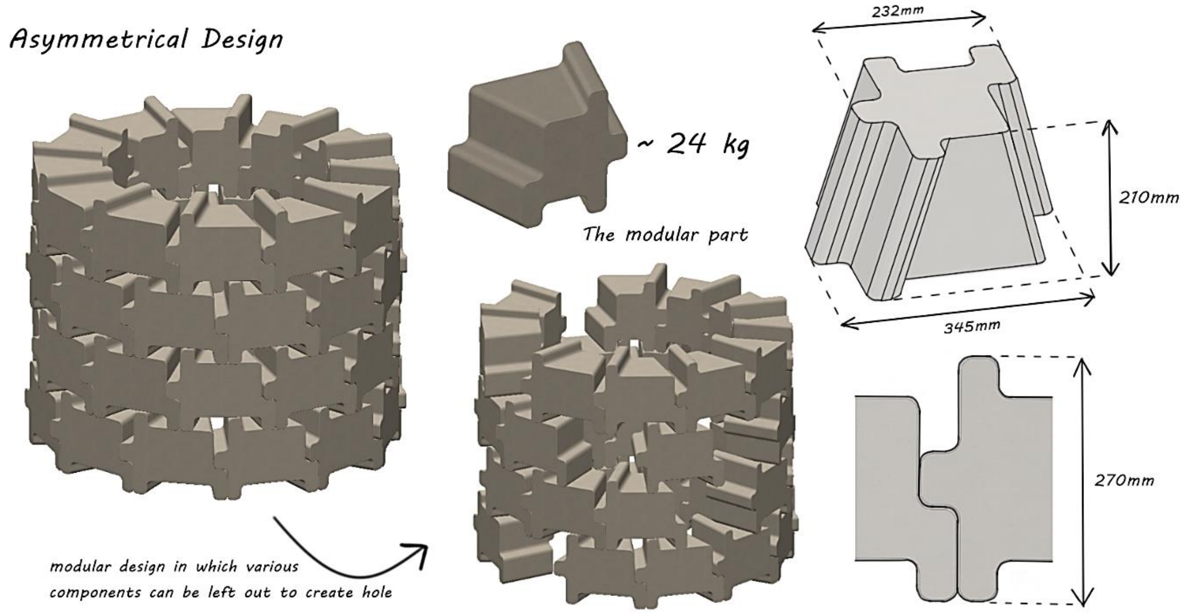
- Each part will be 3D printed with a concrete printer as agreed.
- The composition of the concrete is provisionally fixed for prototype construction but could possibly be changed on advice.
- A maximum height of 300 mm is valid for concrete printing. If this is constructed higher, the chances of printing going wrong are high.
- For a clamping as with hot Puzzle & Lego design, a distance between the two parts of at least 10mm is required, this means a clearance of 5mm at the clamping.
- Because each design is modular and works with clamping, it is possible to leave out several pieces, creating holes for the fish.
- more detail is given for each design in Chapter 9: Solid Works model & technical choices

9.2 Lego design



The overall design has an outer diameter of 1158 mm, its inner diameter is 718 mm. One part of the design has dimensions of approximately: 270x360x210 mm and weighs 27 kg.

9.3 Asymmetrical design



The overall design has an outer diameter of 1158 mm, its inner diameter is 718 mm. One part of the design has dimensions of approximately: 270x345x210 mm and weighs 24 kg.

10. SOLID WORKS MODEL & TECHNICAL CHOICES

A 3D CAD model of the product was modelled in Solid Works and various calculations were made on it. It also explains how the components control each other and clarifies the use of the device. In this chapter, the choice of material for the components is also made clear and the strength of the material and the construction will be examined in order to determine whether the product can hold certain forces.

10.1 The 3D CAD models

The 3D CAD model was modelled in Solid Works. Below a few views of the product including a render. Other images can be found in the appendices.

10.1.1 Puzzle reef

Figure 45: Part Puzzle reef

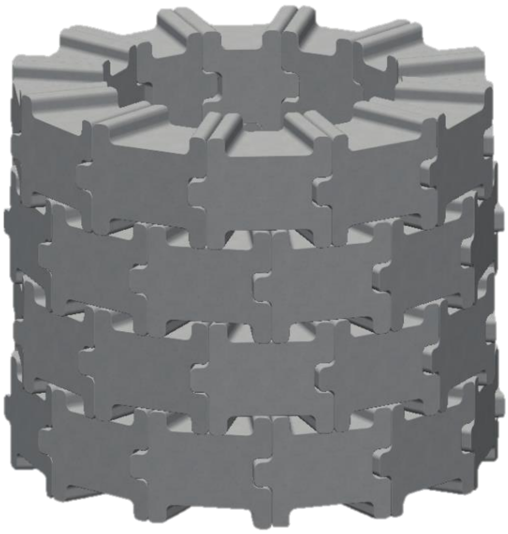


Figure 44: Assembled Puzzle reef

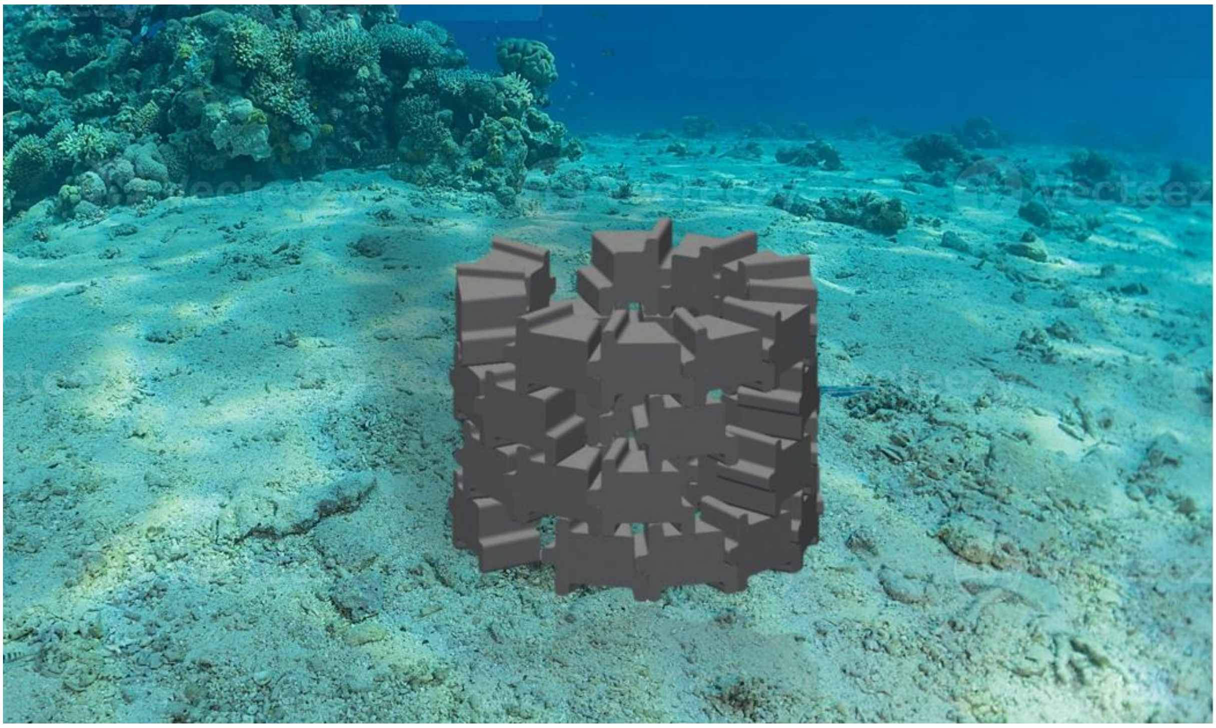


Figure 46: Render Puzzle reef

10.1.2 Lego reef

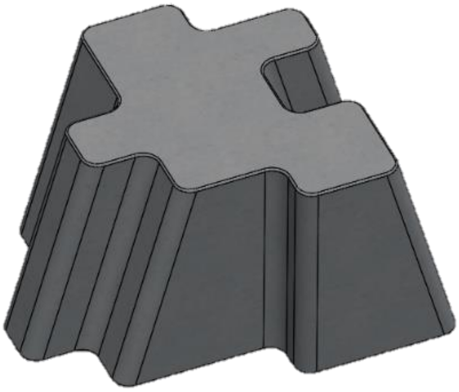


Figure 49: Part Lego Reef

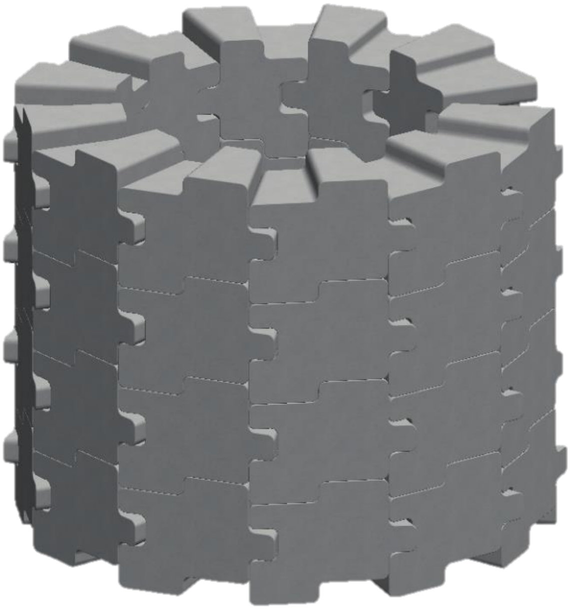


Figure 48: Assembled Lego reef

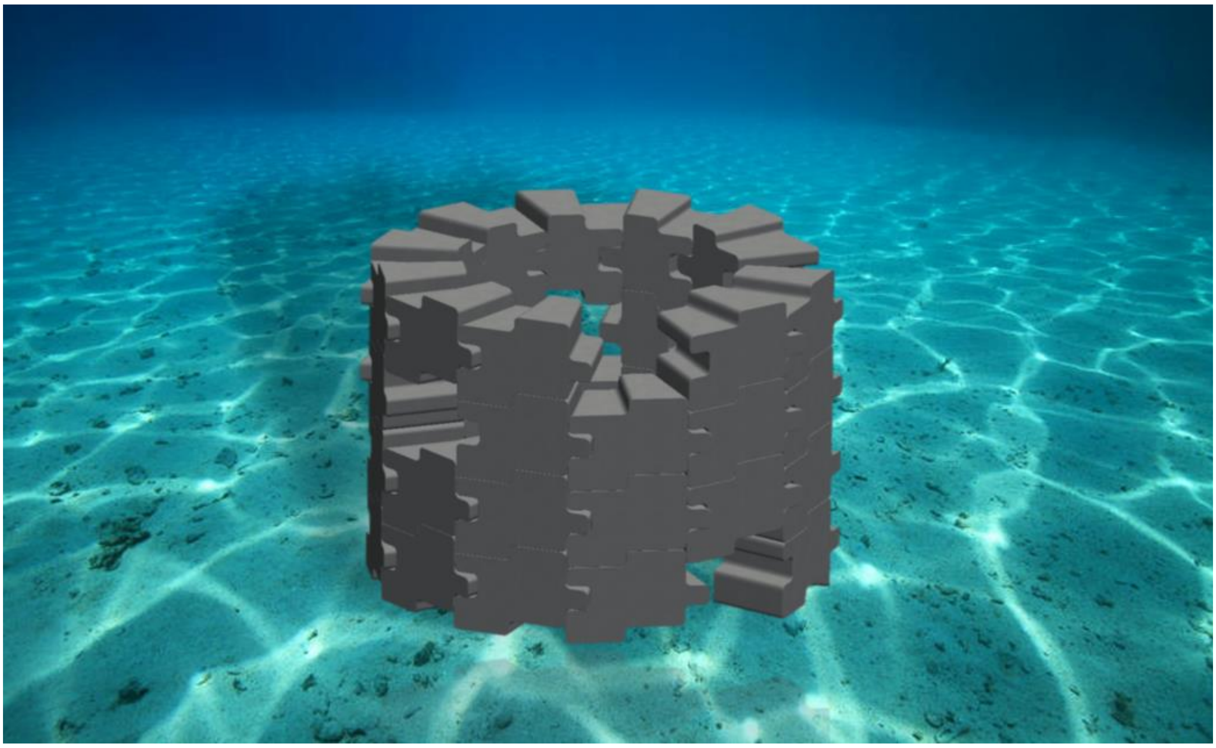


Figure 47: Render Lego reef

10.1.3 Asymmetrical reef

Figure 51: Part Asymmetrical reef

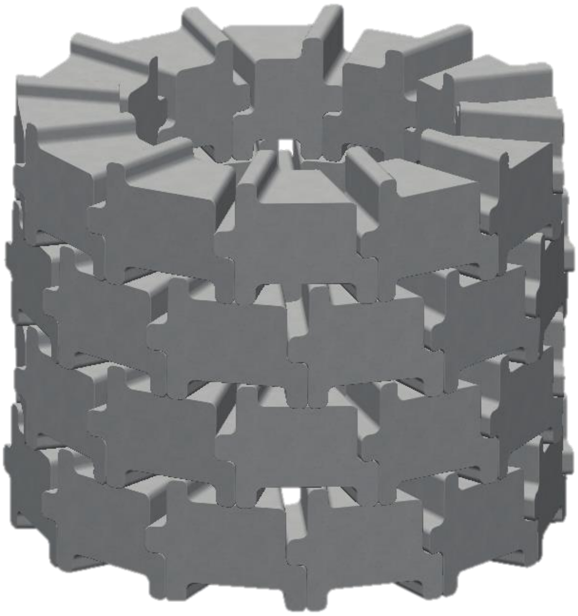


Figure 50: Assembled Asymmetrical reef

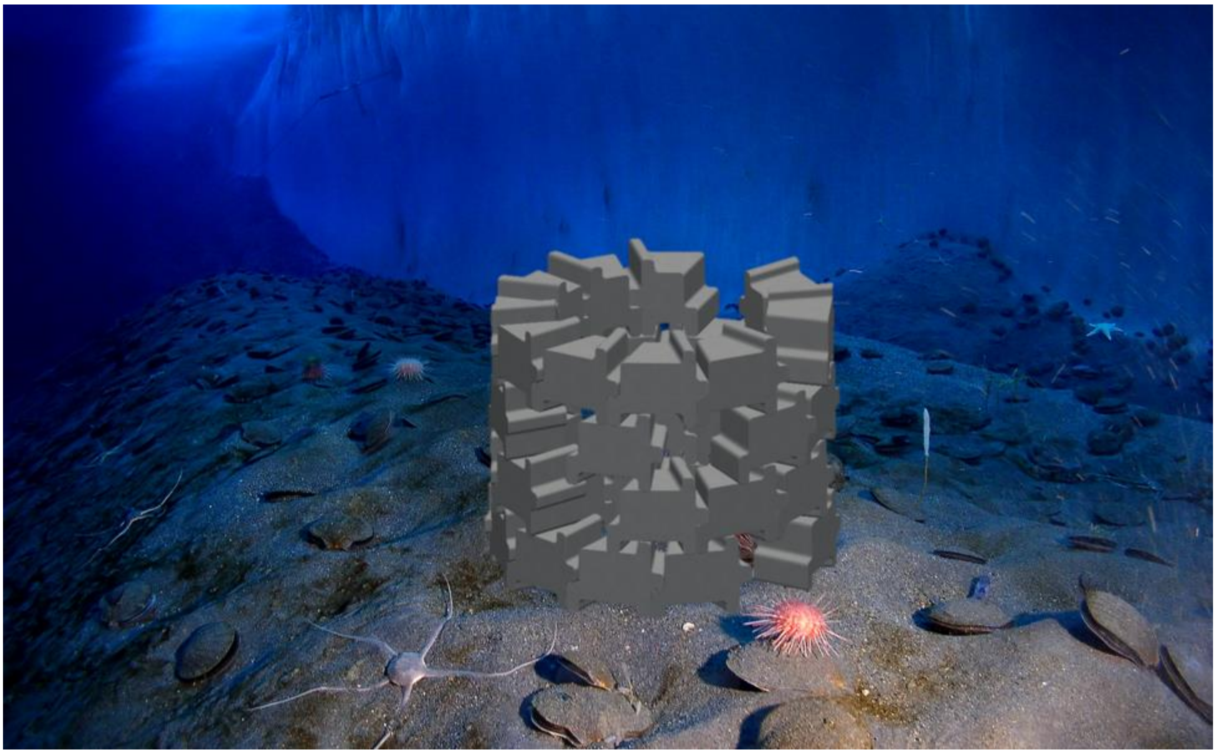


Figure 52: Render Asymmetrical reef

10.2 Technical drawings

A technical drawing in American projection plays a crucial role within a design project. It provides a centralised and detailed representation of the design, allowing designers and engineers to collaborate, establish dimensions, specify parts and ensure the functionality of the final product. It promotes accuracy, consistency and efficiency in the design process.

A technical drawing of each design has been created and is shown below.

10.2.1 Technical drawings in American projection - Puzzle reef

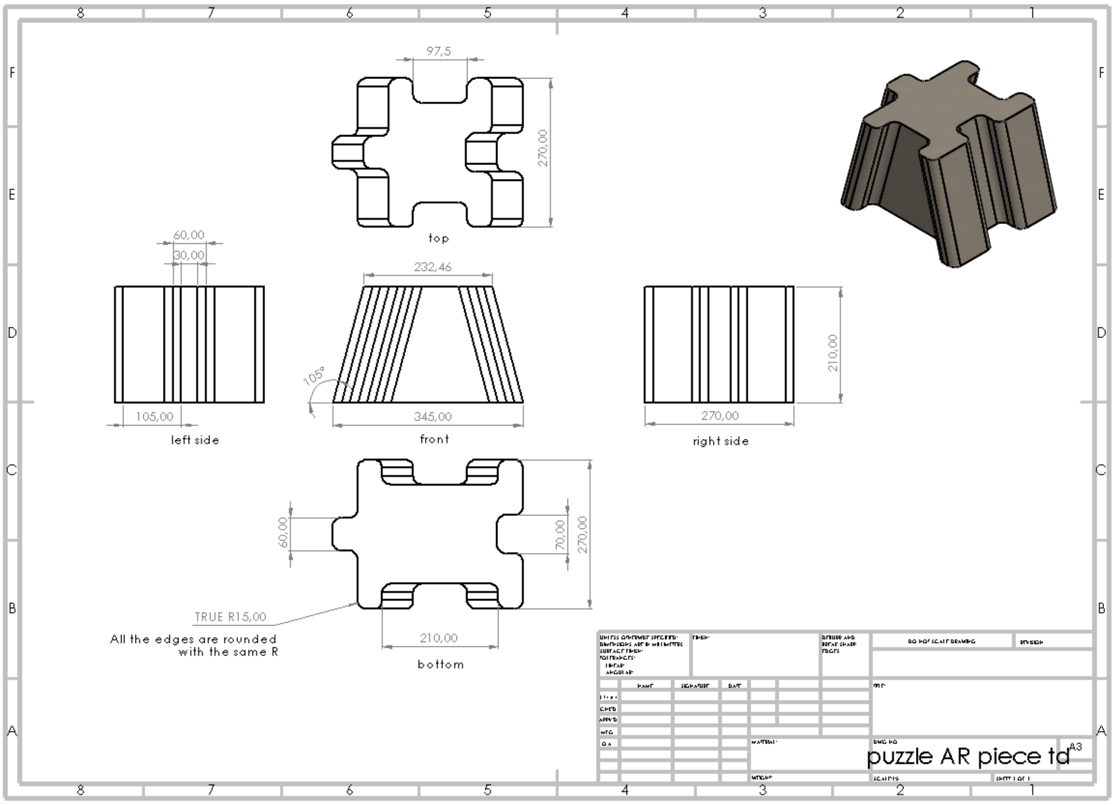


Figure 53: Technical drawing

10.2.2 Technical drawings in American projection - Lego reef

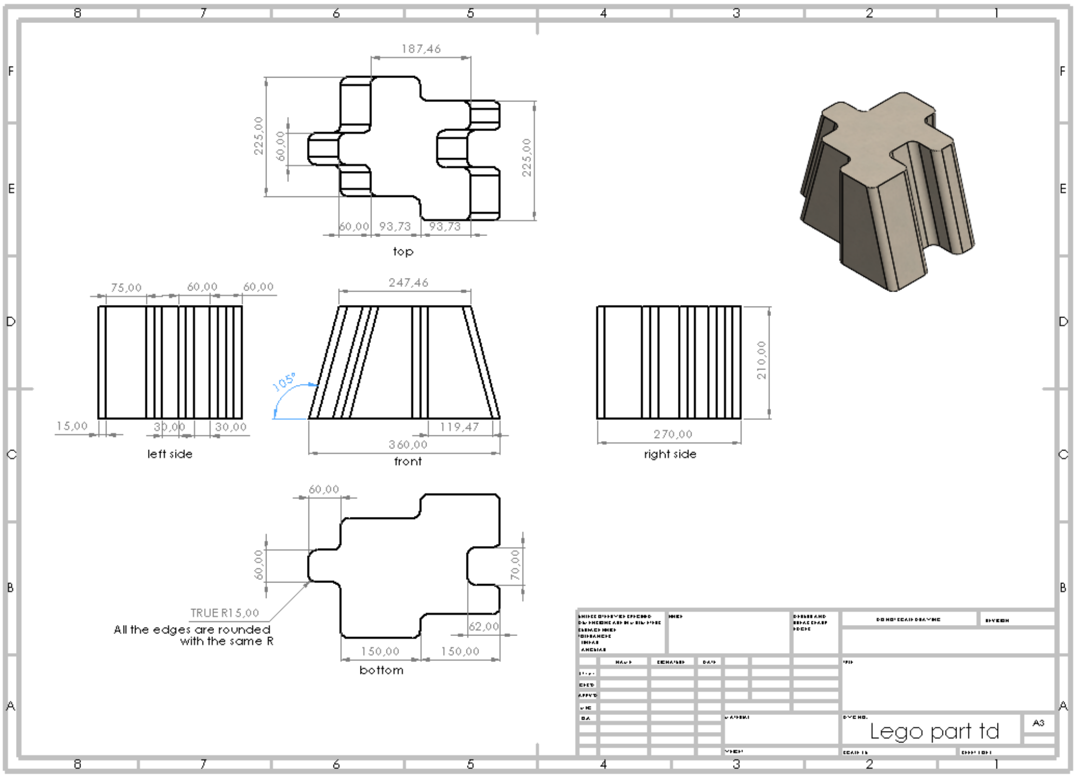


Figure 54: Technical drawing

10.2.3 Technical drawings in American projection - Asymmetrical reef

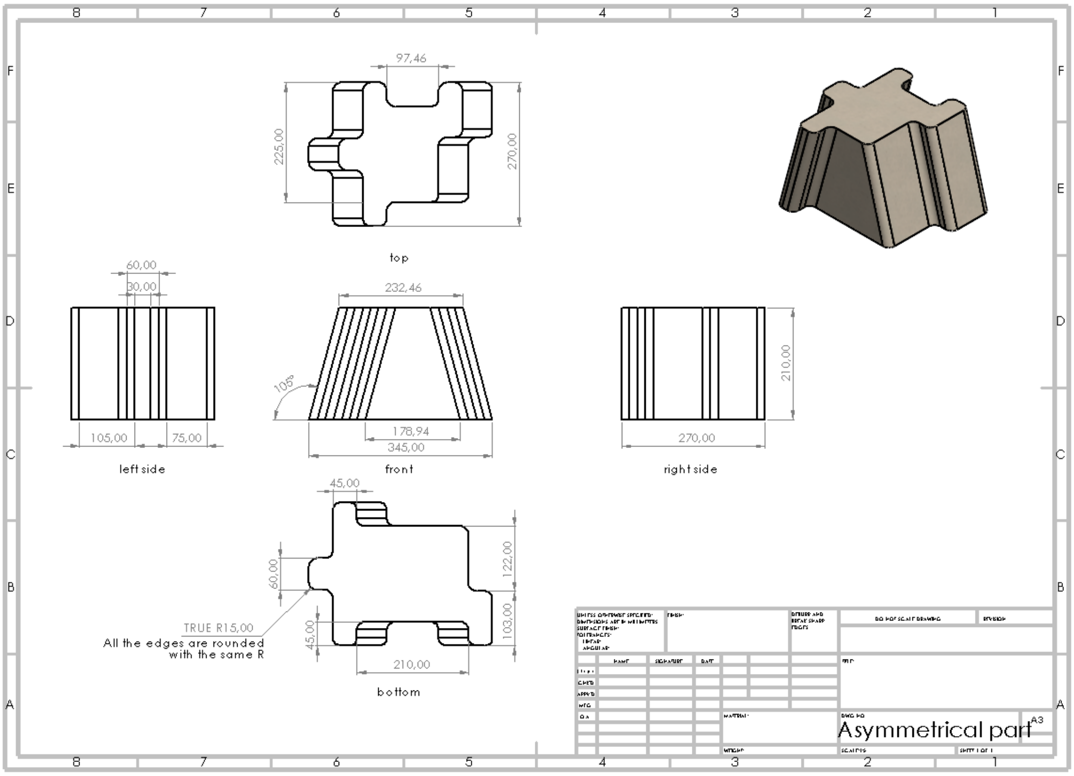


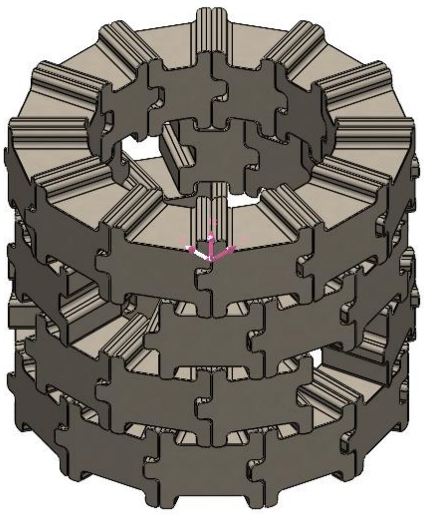
Figure 55: Technical drawing

10.3 Load situation

It is important to know where the greatest forces are within a design to ensure its structural integrity. By identifying these forces, engineers can select suitable materials, apply appropriate reinforcement techniques and avoid structural weaknesses, ensuring the safety and durability of the design.

With the artificial reef, it is important that the centre of gravity is in the middle and as low as possible. The higher this force sits the more unstable the overall design becomes which would like to be avoided. In the following pictures, the centre of gravity is shown.

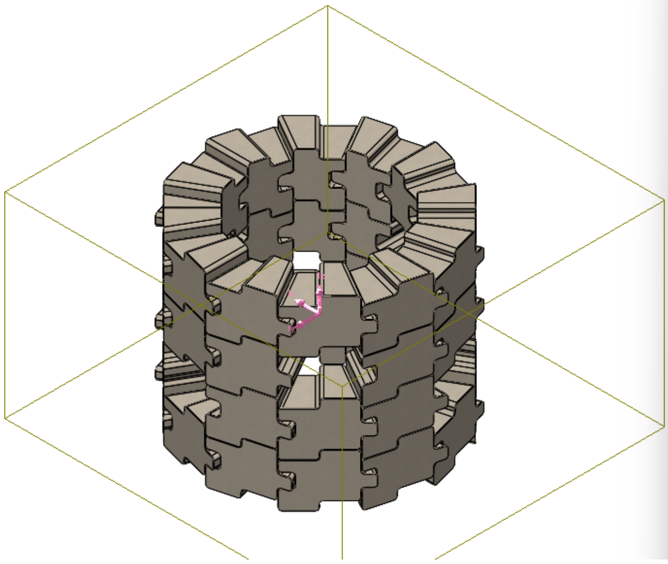
10.3.1 Load situation – Puzzle reef



```
Mass properties of SIMULATION puzzle 4 layers
    Configuration: Default
    Coordinate system: -- default --

Mass = 451316.55 grams

Volume = 451316548.28 cubic millimeters

Surface area = 15521353.97  square millimeters

Center of mass: ( millimeters )
     X = 0.00
     Y = 472.50
     Z = 0.00

Principal axes of inertia and principal moments of inertia: ( grams *  square
Taken at the center of mass.
      Ix = ( 0.00,  0.00,  1.00)        Px = 84121587278.00
      Iy = ( 1.00,  0.00,  0.00)        Py = 84121587278.00
      Iz = ( 0.00,  1.00,  0.00)        Pz = 100776191722.56

Moments of inertia: ( grams *  square millimeters )
Taken at the center of mass and aligned with the output coordinate system
     Lxx = 84121587278.00         Lxy = 0.00                  Lxz = 0.00
     Lyx = 0.00                   Lyy = 100776191722.56       Lyz = 0.00
     Lzx = 0.00                   Lzy = 0.00                  Lzz = 8412

Moments of inertia: ( grams *  square millimeters )
Taken at the output coordinate system. (Using positive tensor notation.)
     Ixx = 184880910427.79        Ixy = 0.00                  Ixz = 0.00
     Iyx = 0.00                   Iyy = 100776191722.56       Iyz = 0.00
     Izx = 0.00                   Izy = 0.00                  Izz = 1848
```

Figure 56: Load situation

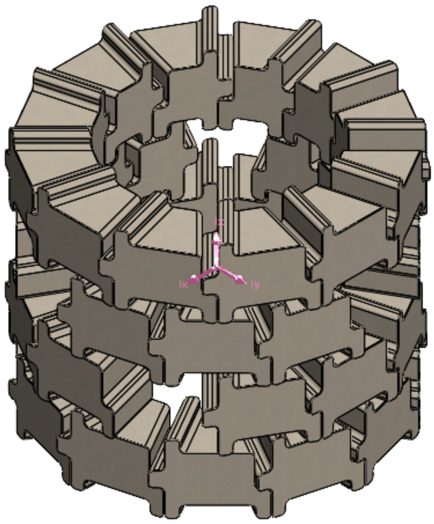
10.3.2 Load situation – Lego reef



```
Mass properties of SIMULATION Lego 4 layers
    Configuration: Default
    Coordinate system: -- default --

Mass = 1093186.22 grams

Volume = 475298358.45 cubic millimeters

Surface area = 14860043.64  square millimeters

Center of mass: ( millimeters )
     X = 0.00
     Y = 472.50
     Z = 0.00

Principal axes of inertia and principal moments of inertia: ( grams *  square
Taken at the center of mass.
      Ix = ( 0.00,  0.00,  1.00)        Px = 204730618913.04
      Iy = ( 1.00,  0.00,  0.00)        Py = 204730644513.55
      Iz = ( 0.00,  1.00,  0.00)        Pz = 244946069742.97

Moments of inertia: ( grams *  square millimeters )
Taken at the center of mass and aligned with the output coordinate system
     Lxx = 204730631713.29        Lxy = 0.00                  Lxz = 0.00
     Lyx = 0.00                   Lyy = 244946069742.98       Lyz = 0.00
     Lzx = 0.00                   Lzy = 0.00                  Lzz = 2047

Moments of inertia: ( grams *  square millimeters )
Taken at the output coordinate system. (Using positive tensor notation.)
     Ixx = 448791302306.46        Ixy = 0.00                  Ixz = 0.00
     Iyx = 0.00                   Iyy = 244946069742.98       Iyz = 0.01
     Izx = 0.00                   Izy = 0.01                  Izz = 4487
```

Figure 57: Load situation

10.3.3 Load situation – Asymmetrical reef



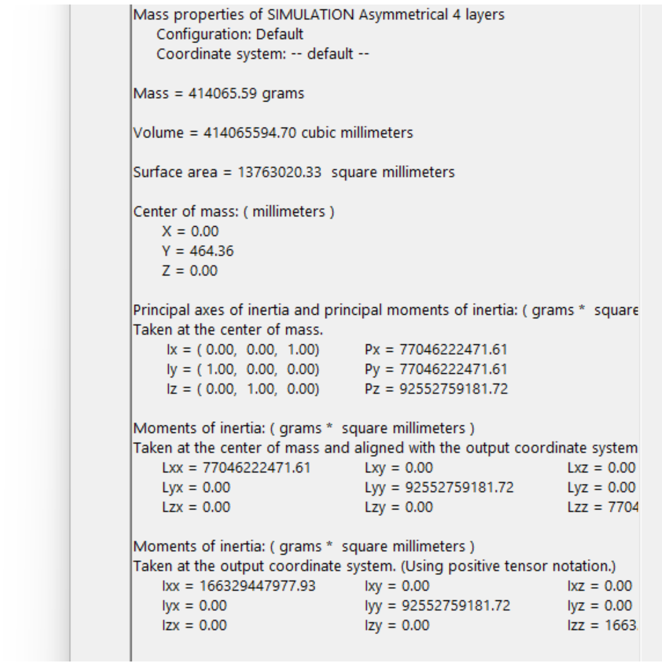


Figure 58: Load situation

10.4 Production method and material choice

In this section, the production method and choice of materials are explained on the basis of various programmes. Three of the eight parts are worked out in detail, while the rest are briefly explained in a table.

10.4.1 PCM drawings (Production, Construction, Material)

PCM drawings are a kind of technical drawings that go into a little more detail on the material - production process combination. PCM stands for Production, Construction, Material. Normally a drawing is made of each component of a product, but since this product consists of only one component that is used more often, only one drawing per design has been created.

In each case, concrete printing is used. If a mould was used with this, a drawing with emission points etc. would also normally be drawn here. That is not the case in this project.

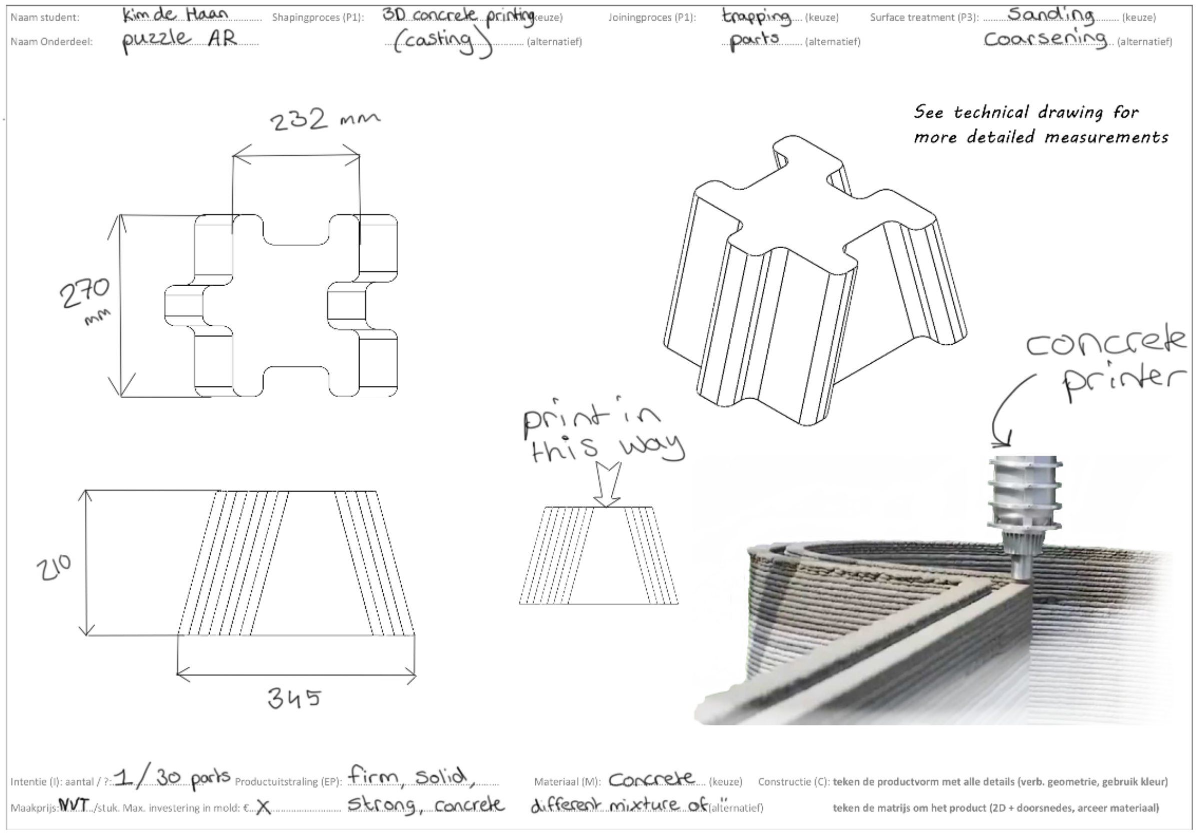


Figure 59: PCM drawing puzzle AR

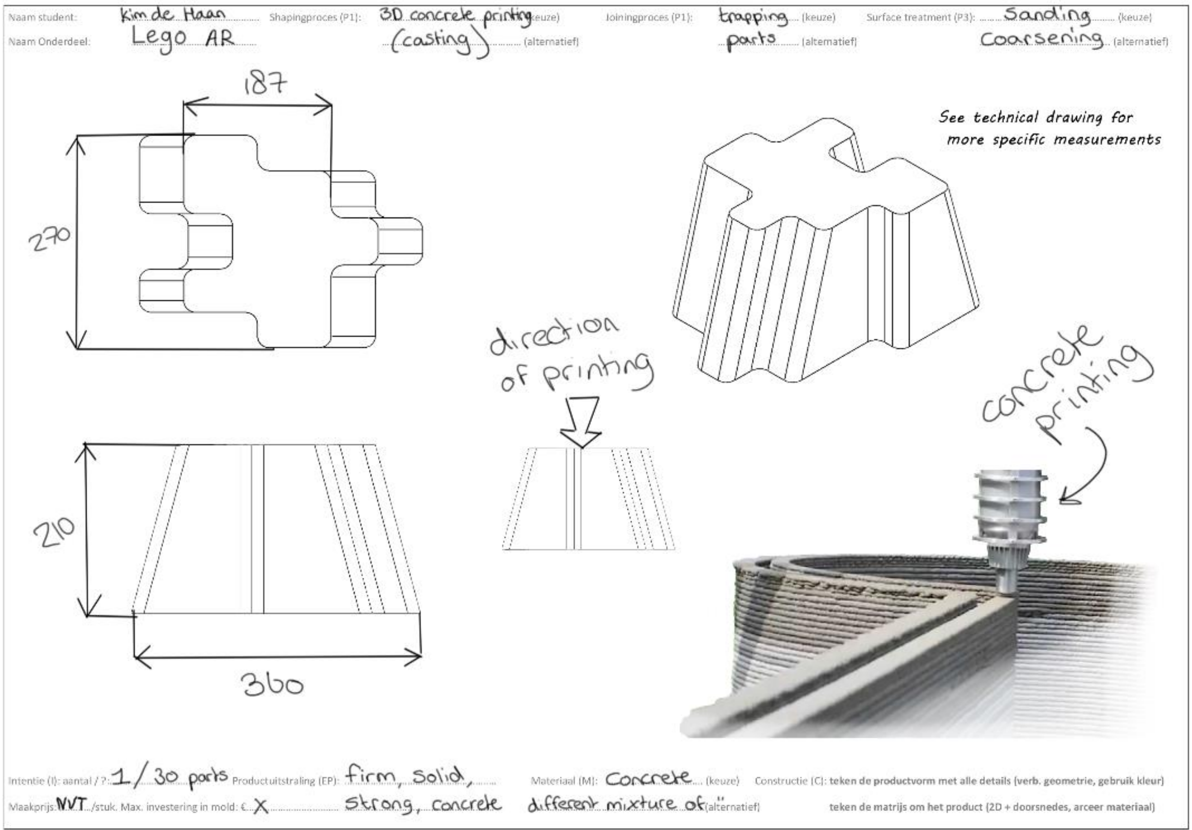


Figure 60: PCM drawing lego AR

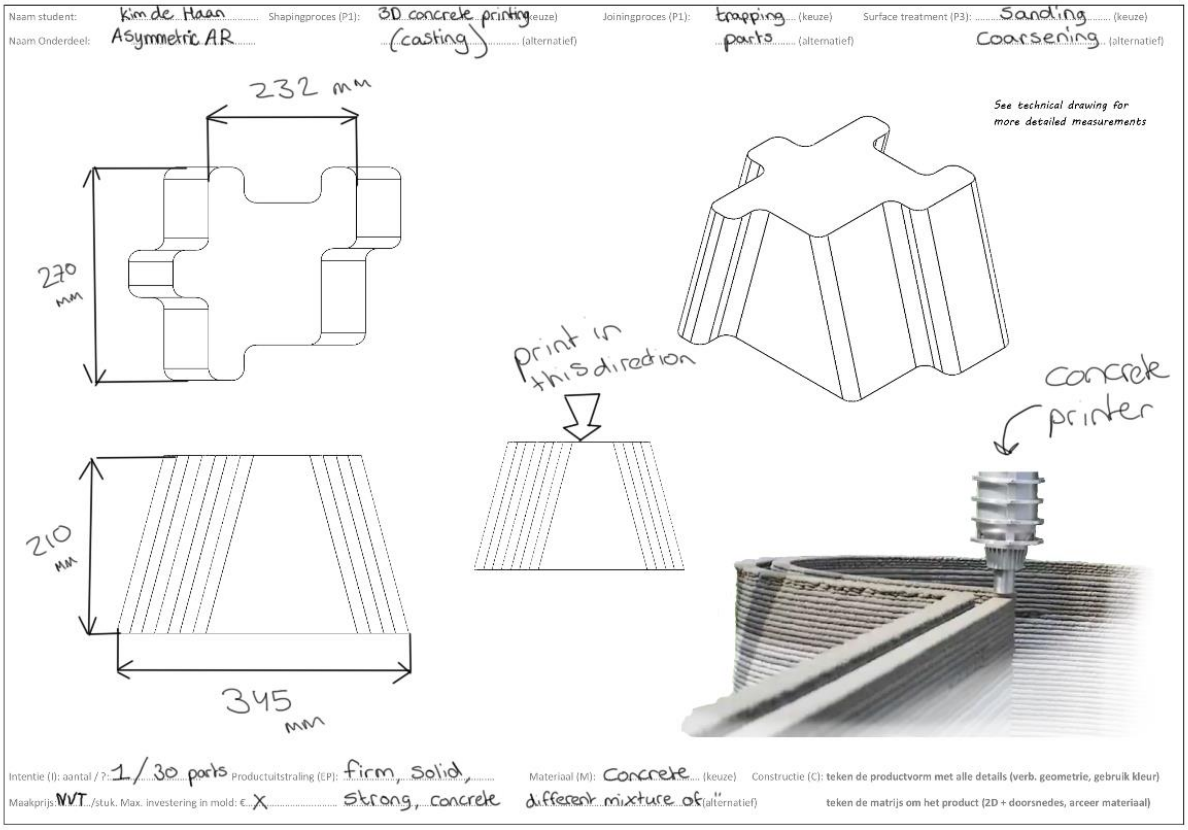


Figure 61: PCM drawing asymmetrical AR

10.4.2. Production method and material choice

The production method used for each design is 3D concrete printing. This is a requirement communicated from the clients, which is why the design is specifically designed for concrete printing.

Since the production process as a requirement is 3D concrete printing, it goes without saying that the material then becomes concrete. To be a little more specific, the concrete used for the design is a mixture made with 20% of water, 24% of cement from Portland, 24% of fine grains of sand with a diameter below 2 mm and 24% of dust. Moreover, chemical components are added in low quantity (around 8%) to improve the consistency. Without it, the consistency will be too liquid and the printer wouldn't be able to print.

11. ECO FOCUSED DESIGNING

Eco-design, also known as sustainable design, is the incorporation of environmentally friendly principles and practices into the design process of products, systems and structures. While an artificial reef may not be directly associated with eco-design at first glance, there are several aspects where eco-design principles can apply. For example, with material selection: when designing and building an artificial reef, the choice of materials can play a role in minimising negative environmental impacts. It is also important to perform a Life cycle analysis. Eco-design considers the entire life cycle of a product or structure, including production, use and final disposal. In the case of artificial reefs, a life cycle analysis can help identify the most environmentally friendly options for reef construction, maintenance and disposal.

By applying eco-design principles to artificial reefs, the negative impact on the environment can be reduced and the reef can make a sustainable contribution to the marine ecosystem. It can help protect natural habitat, promote biodiversity and strengthen ecological resilience. This chapter will therefore look at the life cycle and what environmental impact an artificial reef has through Granta Edupack; the Eco audit tool.

11.1 Life cycle analysis

The life cycle of an artificial reef can vary depending on several factors, including the type of artificial reef, the location, the materials used and the management measures taken. In general, the life cycle of an artificial reef can be divided into the following phases:

Planning and design: In this phase, the objectives of the artificial reef are determined, such as promoting biodiversity, protecting coral reefs or creating a dive site. The reef is designed based on these objectives and taking into account environmental factors.

Construction: After the design is completed, the artificial reef is built. This may involve placing structures such as concrete modules, shipwrecks, boulders or artificial coral structures on the seabed. Construction can take place on land and then be sunk, or built directly into the sea.

Installation: The artificial reef is transported to its intended location and installed. This may mean placing it on the seabed or attaching it to an existing structure, such as a pier or platform.

Settlement: In this phase, life begins to settle on the artificial reef. Algae, corals, sponges and other marine organisms colonise the structure. This process may take some time, depending on conditions, but eventually the reef will support a diverse ecosystem.

Growth and development: As time passes, organisms on the artificial reef grow and the reef develops. Corals can expand and form complex reefs. Fish and other marine animals are attracted to the reef and use it as a food source, shelter and spawning site.

Monitoring and maintenance: During the life cycle of the artificial reef, monitoring and maintenance is essential. Scientists and managers monitor the health of the reef, check for any damage or degradation and carry out restoration work when necessary. This may include, for example, removing unwanted species, repairing damaged structures or adding additional elements to increase diversity.

Evolution and change: Artificial reefs are constantly evolving and undergoing changes as time passes. New species may establish, coral structures may grow and the ecosystem may evolve. The artificial reef can remain for many years or even decades

11.2 Eco audit tool

The Eco Audit tool calculates the consumption and puts it in a clear and comprehensive report. You can do this in the programme: Granta Edupack. This report is visible in the appendices.

The lifespan of an artificial reef can vary depending on several factors. In general, however, an artificial reef can last for many decades. Therefore, it was chosen assuming that the artificial reef lasts a lot longer, weather conditions are increasingly extreme and thus difficult to say how long the reef can last. In a heavy storm, even the slightest movement of the reef could cause damage. [10]

A look was taken at what the energy (MJ) and carbon footprint of each design is for each reef. This involved comparing what it does for a design with 3 layers and 4 layers of components. After this has been done for each design, a conclusion is written and the different results compared.

11.2.1 Puzzle reef 3 layers

To be precise, the production and installation process of the puzzle reef with 3 layers of components has an average energy consumption of 42.5 MJ per year and a CO_2 footprint of 5.5 kg per year.

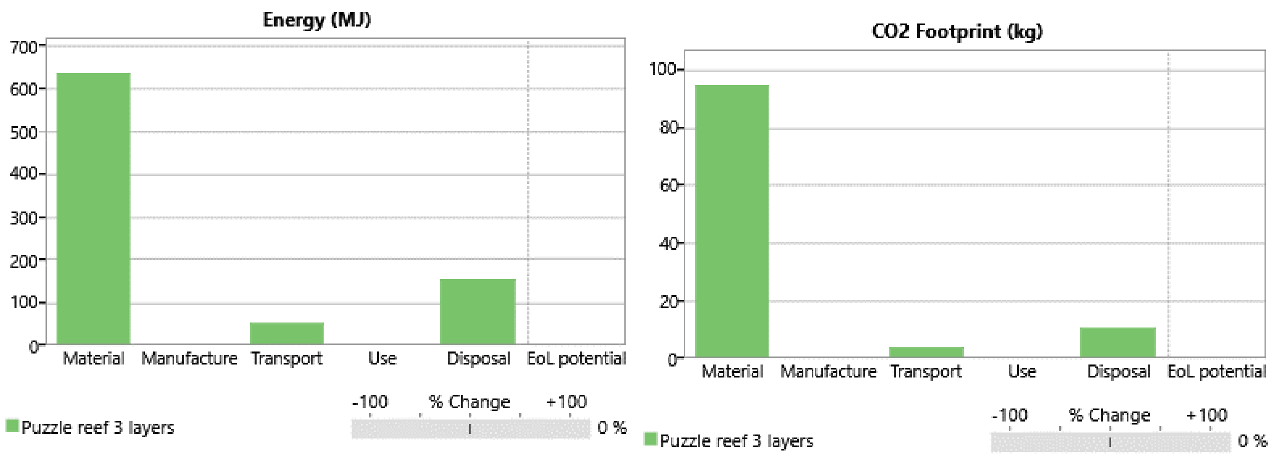


Figure 62: Puzzle reef 3 layers result

11.2.2 Puzzle reef 4 layers

If you were to take the same design (Puzzle) only to do four layers, the production and installation process has an average energy consumption of 59.5 MJ per year and a CO_2 footprint of 7.7 kg per year.

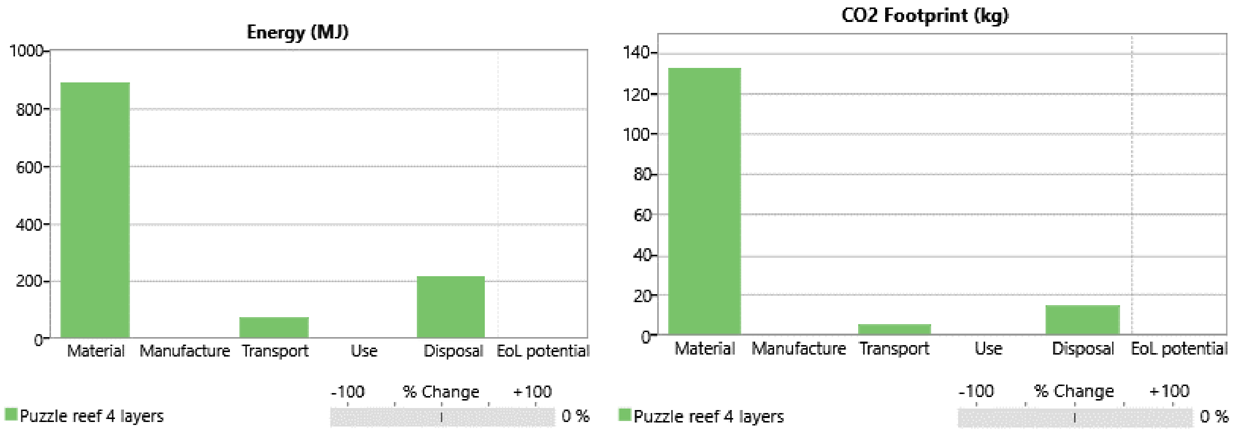
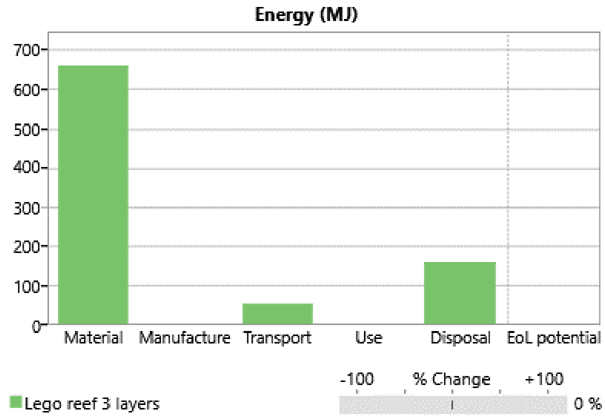


Figure 63: Puzzle reef 4 layers result

11.2.3 Lego reef 3 layers

To be precise, the production and installation process of the lego reef with 3 layers of components has an average energy consumption of 44.2 MJ per year and a CO_2 footprint of 5.71 kg per year.



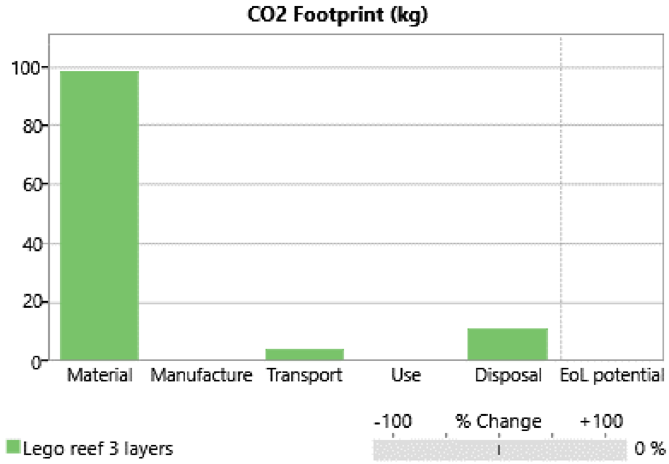
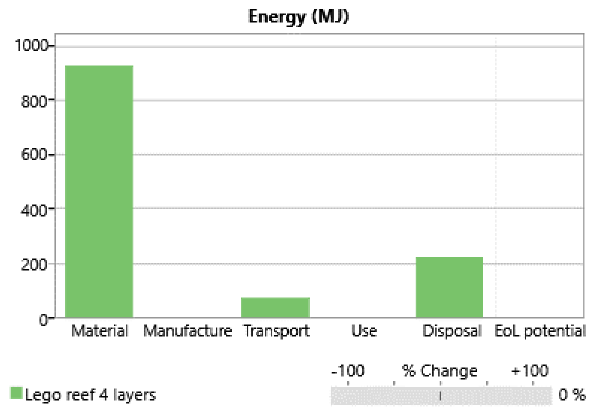


Figure 64: Lego reef 3 layers result

11.2.4 Lego reef 4 layers

If you were to take the Lego design only to do four layers, the production and installation process has an average energy consumption of 61.8 MJ per year and a CO_2 footprint of 8.0 kg per year.



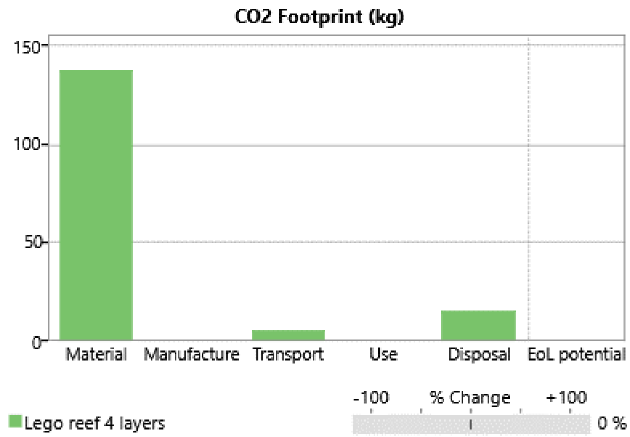
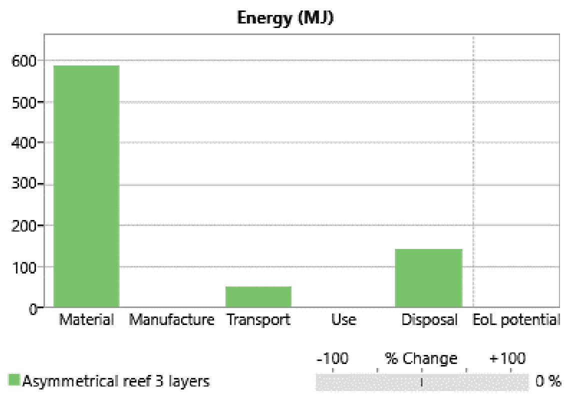


Figure 65: Lego reef 4 layers result

11.2.5 Asymmetrical reef 3 layers

To be precise, the production and installation process of the asymmetric reef with 3 layers of components has an average energy consumption of 39.3 MJ per year and a CO_2 footprint of 5.08 kg per year.



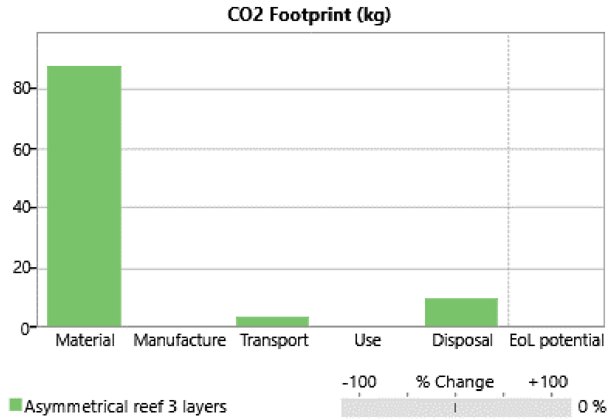


Figure 66: Asymmetrical reef 3 layers result

11.2.6 Asymmetrical reef 4 layers

If you were to take the same design (Asymmetrical) only to do four layers, the production and installation process has an average energy consumption of 55.0 MJ per year and a CO_2 footprint of 7.12 kg per year.

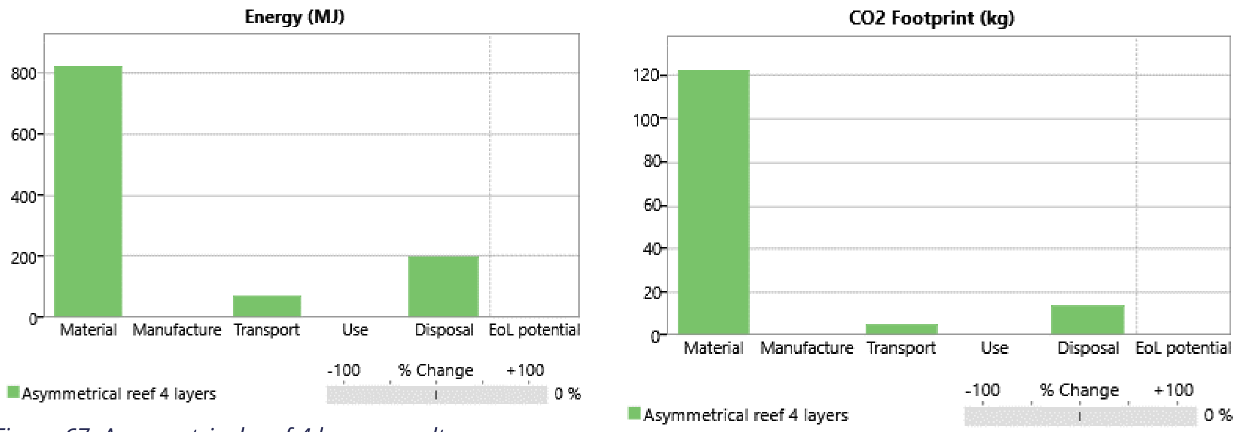


Figure 67: Asymmetrical reef 4 layers result

11.3 Eco designing conclusion

So, per kilogram of concrete, about 18.35 MJ of energy is consumed per year if you assume a 20-year lifespan. Therefore, if a longer lifespan is introduced, the energy consumption per year will decrease since no energy is used during use (after installation of the artificial reef).

The CO_2 footprint averages 141.82 kilograms per year. Here too, the longer the lifespan becomes, the smaller the footprint becomes per year.

This has all to do with the material. In fact, the production of concrete is not a sustainable process. The material itself can be made more sustainable by using recycled materials, but mixing the components inside concrete is a polluting process. With this, the more materials used, the higher the energy consumption and CO_2 footprint become. The Eco Audit tool does not yet take the production process into account; if the design is 3D printed, the values will increase even more.

After production, the components must also be brought to the OBSEA centre. That means it must first be transported by small bus from the UPC in Terrassa to the port in Vilanova i la Geltru. This is 73 km in total. Then it also has to be transported to the lab in the sea by boat, this is 20 km in total. Since the design is modular, a smaller truck can be used to transport it and this means it is also a bit more sustainable.

Since the artificial reef consumes no energy during use, it is set to 0.

Finally, when the design reaches the end of its lifespan, it has to be disposed, concrete can be ground up and used for new concrete structures, but the material will never be completely decomposed. Again, the more material used the higher the value for disposal.

12. VALIDATION

In this chapter, the cost per component has been looked at and what the price of the product will be. Also, by using a risk analysis, it examines what kind of risks may occur to the product.

Finally, a check is made as to whether the product meets all the requirements. A risk analysis is carried out and finally a conclusion is drawn as to whether this product fulfils the assignment or not, and recommendations are also made.

12.1 Cost price

To get an idea of production costs, several parameters need to be taken into account:

- The cost of materials
- The production costs
- The labour

12.1.1 Material costs

As it has been said in the paragraph 10.4.2, the pieces of the reef are made of concrete that include cement but also aggregates, filler and chemical additives. Every component is delivered together in a single bag.

For a batch which create around 45kg of concrete, so 9kg of water and 36kg of material, the different components are costing: 5€ for the cement; 1€ for the aggregates; 3€ for the filler; 10€ for the additives. Water has a price that falls around 2€ per m^3 in Spain but in Catalonia the price is 2,68 €/m^3 [11]. Therefore, the price for a batch of concrete is 0,016€ for water and 19€ for material being 19,02€.

The previous prices were determined for a piece fill in at 100%. In order to consume less, it has also been considered to fill in the piece with only 70% of concrete. Consequently, the prices are not the same.

Part		**Weight**	**Filling**	**Price**
Puzzle part		26 kg	100%	10.99 €
		18,2kg	70%	7,69€
Lego part		27 kg	100%	11,41€
		18,9 kg	70%	7,99€

Asymmetrical part		24 kg	100%	10,14 €
		16,8 kg	70%	4,06€

12.1.2 Production costs

The production costs include the costs of the machine, the ones of different testing, the electricity and the time spend by people to make the printer work.

The project being in close collaboration with Terrassa's university, the printer used is already in the building so it won't cost anything. Regarding the electricity costs, the average price is 0,4€ per KWh in Terrassa [12]. Knowing that and the power used by the printer which is really low, the electricity cost is not relevant here.

The printing tests along with the material lost should be take into consideration however at the time being it is difficult to know this amount of material for testing. The material lost should be low because of the industrialisation chosen. Due to choosing 3D printing, every inch of material is used to the piece of the design and nothing else.

The costs of the labour include the time spend busy with the preparation and the machine. In fact, the machine needs to be monitor at all time because the printer cannot print alone. First people need to assembly the component for 30 minutes. Then for 20 minutes they prepare the mixture. Finally, the printer can print and 3 people need to do all the duties in which is prepare another batch. Considering this all, the workface's cost are 3 people paid for the time of printer plus one hour of preparation.

12.1.3 Estimation for one reef

To assess the price of one reef, every cost must be added together. Regarding the material costs, the heaviest piece will be the reference because it will also be the more expensive. The design is made with 42 pieces for the tallest, so in all the price is around 483€. To that must be added the cost of production, labour and transport.

12.1.4 Cost price conclusion

After analysing the costs of every parameter, the price of a reef can be estimated around 483€. It is important to note that the costs do not include the transportation of the reef to its location. Finally, by studying each design, the range of price vary of 1€ but the less expansive one is the model 3, "Asymmetrical" with a price of 10,14€. However, the model 3 has been left out due to its lack of stability. Therefore, the less expansive model is the model 1 "Puzzle" with a price of 10,99€.

12.2 Calculations

To determine which design has the greatest impact on marine biodiversity in terms of energy input, nutrient supply, and habitat provision, relevant calculations are crucial. In this regard, the AREIT index serves as a valuable tool for comparing designs.

12.2.1 What is AREIT index?

Over the past few decades, there has been increasing interest in the use of artificial reefs (ARs) as a tool for marine ecosystem conservation and restoration. The implementation of ARs is a complex task that requires careful consideration of various factors, including the design, construction, and deployment of the structure. To aid in the decision-making process, numerous studies have investigated the impact of ARs on the marine ecosystem and have proposed different metrics for evaluating AR performance. One such metric is the Autotrophic Resource Enhancement and Improvement Tool (AREIT) index, which was developed to assess the ability of ARs to improve energy, nutrient, and habitat availability for marine organisms. In this context, several studies have contributed to the development of the AREIT index, including work by Kuffner et al. (2017), Gato et al. (2019), and Diaz et al. (2021), among others. These studies have provided valuable insights into the design and performance of ARs and have helped to establish a framework for evaluating ARs using the AREIT index. [13]

AREIT is a comparative tool developed to assess the potential positive impact of artificial reefs (ARs) on the ecosystem in territorial seas. It measures the performance of an AR design compared to a reference design with the same volume in terms of energy, nutrient, and habitat improvement. It allows decision makers to identify the design that generates the highest positive impact on the ecosystem.

The AREIT index is a valuable tool to assess the overall performance of artificial reef (AR) designs, but it is important to understand the contribution of each of the three partial indices.

The Energy Modification index (EM) assesses the potential increase in primary productivity that can be achieved through the design of the AR. This is determined by the amount of surface area that is exposed to sunlight and the associated increase in photosynthesis. Therefore, the EM indicates that increasing the number of exposed surfaces, such as vertical walls, can lead to an increase in primary productivity. This can be achieved by incorporating features such as caves, overhangs, and niches that increase the effective surface area and create more opportunities for organisms to colonize and grow.

$$EM = \frac{Sv.fev + Sh.feh}{Svr.fev + Shr.feh} \qquad (1)$$

The Nutrient Modification index (NM) focuses on the role of the AR in nutrient cycling. It is determined by the amount of upwelling and back eddy effects that the AR design introduces into the ecosystem. Increasing the number and size of the lateral holes can lead to a higher permeability effect, which can reduce upwelling and back eddying. This reduces the effectiveness of the AR in facilitating nutrient cycling. Therefore, it is important to maintain an appropriate ratio of vertical surfaces to lateral holes to ensure that the AR can effectively facilitate nutrient transfer.

$$NM = \frac{Supwelling}{Supwelling\_r} \qquad (2)$$

The Habitat Modification (HM) assesses the potential for the AR to provide new habitats for marine organisms. This is determined by the number of new cavities and crevices that the AR design provides. Increasing the number and size of the cavities can lead to a higher potential for the AR to provide shelter and breeding grounds for marine organisms. The roughness factor for the vertical surfaces also plays an important role in determining the habitat potential of the AR. A higher roughness factor can provide a better attachment surface for marine organisms, increasing the potential for colonization and growth.

$$HM = \frac{Snest\_cavities}{Snest\_cavities\_r} \qquad (3)$$

Each partial index formula is a ratio, or division, between the partial index for a specific AR design and the partial index for a reference design with the same volume. If the ratio is greater than 1, it means that the specific AR design is better than the reference design in terms of its impact on the ecosystem.

$$AREIT = EM + NM + HM \qquad (4)$$

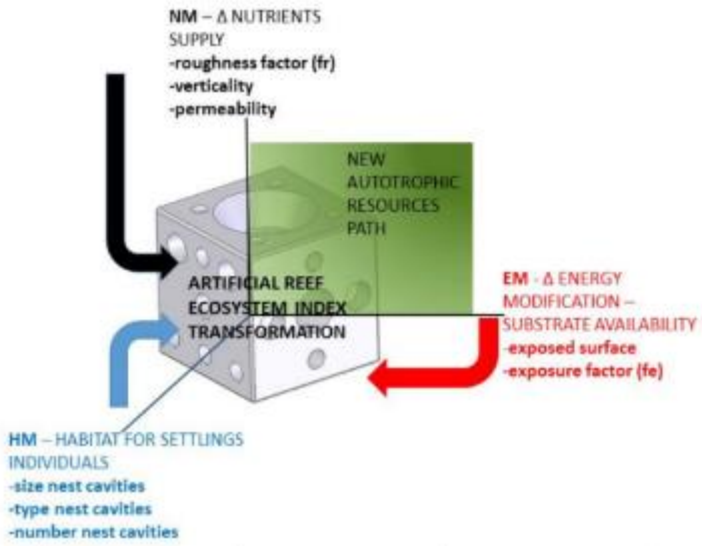


Figure 68: Graphical representation proposal for the AREIT partial indices: EM (energy modification), NM (nutrient modification) and HM (habitat modification) including the most important factors that affect each one of the indices

If the AREIT index is greater than 3, it indicates that the overall performance of the AR design is better than the reference design. This means that the AR design has a higher positive impact on the ecosystem, in terms of increased energy, nutrient availability, and improved habitat. A high AREIT index reflects the ability of the AR design to significantly contribute to ecosystem enhancement in the context of sustainable development.

When using the AREIT index, it is important to note that each partial index should ideally be greater than 1, indicating an improvement compared to the reference design. However, it is entirely possible for not all partial indices to exceed 1, and this is not necessarily a problem. Depending on the study conducted or the objective pursued, the focus may be on enhancing a single or specific factors, rather than increasing the efficiency of all factors simultaneously. Each ecosystem is unique and may have specific needs. The AREIT index provides a comparative measure to assess the overall impact of an AR design compared to a reference design, taking into account the different dimensions of energy, nutrients, and habitat.

In conclusion, designing an effective artificial reef requires careful consideration of each of the three partial indices. The Energy Modification index highlights the importance of maximizing the number of exposed surfaces to increase primary productivity. The Nutrient Modification index emphasizes the need to balance the ratio of vertical surfaces to lateral holes to facilitate nutrient cycling. The Habitat Modification index underscores the importance of providing new cavities and crevices to increase the potential for the AR to provide new habitats for marine organisms. Understanding the contribution of each partial index can help guide the design of ARs that achieve the greatest positive impact on the ecosystem per unit of volume.

It is important to note that AREIT is a comparative parameter, and comparing designs with significantly different sizes and volumes using this indicator can lead to incorrect conclusions.

Overall, the AREIT index is a comparative tool that helps decision-makers choose the AR design with the greatest positive impact on the ecosystem per unit of volume. By using this index, it is possible to compare the performance of different AR designs based on their impact on energy, nutrients, and habitat, while taking into account factors like size and material.

12.2.2 Calculation of AREIT index

To calculate AREIT index with 4 designs, it must have been done step by step. To have a better understanding, the next steps will focus on one design. At first, every surface of each face of one piece has been calculated. After that, in the entire design, it was necessary to seek for other parts sticking out the design. These parts are being called “surplus” on the excel table visible in the appendix. For each surplus out had a reverse one in the inside that was also take into account. Their surfaces were also measured. Then, on the full design, every piece, every surplus and every hole were counted to simplify the next calculations. In order to calculate EM index (a part of the AREIT index), the horizontal and vertical surface had to be separated. So, with the previous surfaces and the number of pieces and holes it was easier to calculate the horizontal and vertical surface. One point that needs to be noted is the holes are counted in the total surface and in the hole surface. Therefore, the hole surface must be separated in two parts: one for the horizontal surfaces and another one for the vertical surfaces. When every calculation is done, the parameters of Sv, Sh and the surface of different holes were found.

Finally, since the others parameters are constant the same operations can be repeated for each design and AREIT index can be determined.

12.2.3 Comparison of the designs

In the previous designs made it was decided not to create any cavities to simplify as much as possible the printing. This decision impacts the AREIT index because the ratio HM (Habitat Modification) is equal to 0. Therefore, the AREIT index will bring a conclusion at 2 and not 3 as it had been said before.

To read the table, the vertical line contains the information of the pieces considered as a reference and the horizontal columns are the ones that are being compared with.

normal / ref	PUZZLE 4 layers	PUZZLE 3 layers	LEGO 4 layers	LEGO 3 layers
PUZZLE 4 layers		1,400	1,529	1,666
PUZZLE 3 layers	2,646		2,394	2,166
LEGO 4 layers	2,687	1,753		1,900
LEGO 3 layers	2,646	1,847	2,21367767	

Table 2: Results of the AREIT index

Every number above the value 2 has been highlighted in green to give a better vision of which design is better. The column *Puzzle 4 layers* has all the values highlighted with green, that results in meaning that this model gives better results than the other ones since the AREIT index is always above the value 2. The design *Lego 4 layers* is the second best since it can be observed that it has twice an AREIT index above 2. In contrast, the design *Puzzle 3 layers* does not have any highlighted square, that suggests that this model could be the worst from all.

12.2.3 Calculation's conclusion

As it can be observed in the table, the Model 1 ("Puzzle") that contains four layers stands out when it is being compared to the other designs. As a contrast, the version of three layers of this design, gives the worst results.

Moreover, the designs with four layers give better results compared to the ones with three layers. However, a clear conclusion cannot be done between the Model1 ("Puzzle") and Model 2 ("Lego") as the Model 1 with four layers gives a better outcome, but when comparing the ones with 3 layers, the other model results as a better option.

As a result, the comparation between models suggests that Model 1("Puzzle") would be a better option when it comes to create structures of four layers. On the other hand, when a structure made up with three layers is created, Model 2 is the one that gives a better performance.

12.3 Simulations

12.3.1 Hydrodynamic Analysis of Current Velocity for Assessing Artificial Reef Stability

As part of the artificial reef design project, hydrodynamic simulation plays a crucial role in assessing the stability of the structure. To conduct this simulation successfully, certain data is indispensable, including current velocity. Analysing the values of current velocities in all directions is essential to evaluate the stability of the structure.

Access to relevant data was obtained through the SARTI company's website. The data was collected using OBSEA sensors positioned at a depth of 19 meters in the targeted area for implementing the artificial reef. The available data encompasses currents in the northward, eastward, and upward directions.

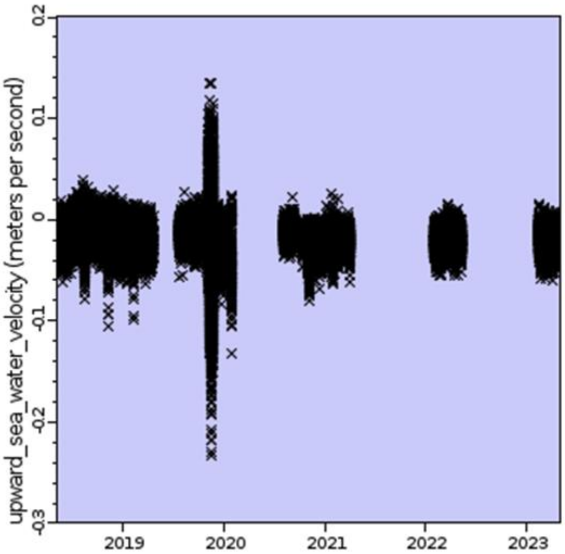


Figure 69: Upward Sea water velocity (m/s) from May 2018 to May 2023

It is important to note that current values can be both positive and negative. For example, in the northward velocity of the water graph, positive current values indicate a northward flow, while negative values indicate a southward flow.

It is also worth noting that the available data does not exhibit complete regularity over the past five years. Certain sensors were temporarily out of service during maintenance periods. Despite these limitations, all accessible data for the study have been used. A notable observation from the graph is the presence of extremely high current velocities at the end of 2019 compared to the rest of the studied period. This increase can be attributed to a severe storm that occurred during that time.

In the context of the study on the stability of the artificial reef, the collection and analysis of maximum current values over a five-year period are of significant importance. The recorded data, along with statistical calculations such as the mean, quartiles, and median, have provided crucial information to evaluate the hydrodynamic response of the reef structure to environmental conditions.

The measurement of monthly maximum current values enables the consideration of the most extreme conditions to which the reef may be exposed. These maximum values represent critical scenarios where hydrodynamic forces are potentially the most intense. Through the analysis of these extreme values, the structural resilience of the reef can be assessed in exceptional situations such as major storms or strong currents. The maximum and minimum values of each month were recorded and compiled into an Excel table for the purpose of conducting the relevant statistical analysis. These values, representing the extremes of each month, were utilized in the statistical calculations.

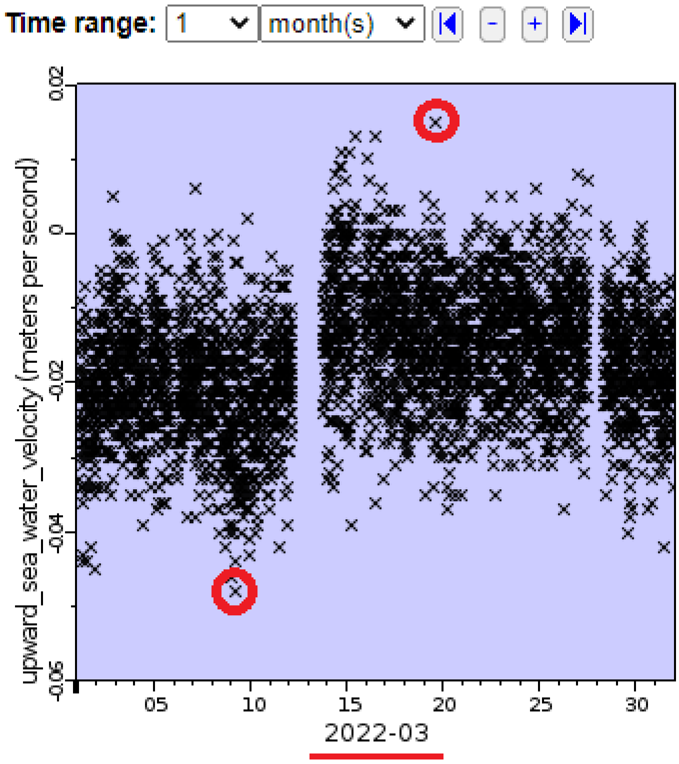


Figure 70: Upward Sea water velocity graph (m/s) March 2022

In addition to the maximum values, the utilization of statistical measures such as the mean, quartiles, and median enhances the understanding of the typical current conditions experienced by the reef. The mean provides an overall estimation of the average current velocity, while the quartiles delineate threshold values that encompass 75%, 50%, and 25% of the current data. These statistical measures allow for comprehending variations and general trends in current velocities over the duration of the study.

Through the integration of all this information, a comprehensive assessment of the hydrodynamic stability of the artificial reef can be conducted. The incorporation of maximum values, statistical measures, and the analysis of typical conditions provides valuable insights into the environmental constraints encountered by the reef. This approach facilitates the design of a robust and resilient structure capable of withstanding a wide range of hydrodynamic conditions while ensuring stability within the reef ecosystem.

Thus, the collection of maximum current values and the use of relevant statistical calculations are crucial steps in the study as they provide essential information to evaluate the hydrodynamic stability of the artificial reef and ensure its resistance to the most extreme environmental conditions.

	Upward current	Northward current	Eastward current
min	-0,233	-0,654	-0,835
max	0,135	0,61	0,299

Table 3: Strongest currents (hurricane: October 2019 to January 2020) (m/s)

	Upward current	Northward current	Eastward current
min	-0,095	-0,3	-0,545
max	0,038	0,195	0,28

Table 4: Strongest currents of the 5 past years (without the hurricane)

	Upward current	Northward current	Eastward current
First quartile	0,01	0,13	0,15
Median	0,017	0,1475	0,18
Third quartile	0,23	0,16	0,21375
Mean	0,0155	0,1435	0,18
90 percentile	0,033	0,193	0,25

Table 5: Statistical calculation from the monthly MAX currents during the 5 past years

	Upward current	Northward current	Eastward current
First quartile	-0,05	-0,1725	-0,2415
Median	-0,058	-0,21	-0,27
Third quartile	-0,0675	-0,2525	-0,38
Mean	-0,067	-0,225	-0,316
90 percentile	-0,091	-0,297	-0,462

Table 6: Statistical calculation from the monthly MIN currents during the 5 past years

Mean of the 90th percentiles MAX:

$$Mean\ 1 = \frac{(0.33+0.193+0.25)}{3} = 0.159 \qquad (5)$$

Mean of the 90th percentiles MIN:

$$Mean\ 1 = \frac{(-0.091-0.297-0.462)*(-1)}{3} = 0.283 \qquad (6)$$

Global mean of the 90th percentiles:

$$Global\ mean\ = \frac{0.283+0.159}{2} = 0.221 \qquad (7)$$

12.3.2 OrcaFlex Simulations

The simulations conducted for the project utilized OrcaFlex 11.3. This step was playing a crucial role during the development of the final designs, which played a crucial role in the development of the final designs. This software provided the opportunity to test the models by replicating various real-world scenarios with exceptional accuracy. As a result, it allowed for the prediction and understanding of the prototype's behaviour. By doing the simulations it was possible to obtain various insights into the performance, reliability, and safety of these project. This resulted as a reduce reliance on costly and time-consuming physical prototypes, that was one of the main goals of the project.

After the analysis of the data provided by the OBSEA sensors, it was possible to put an accurate value to the different parameters of the simulation. In order to create the most real scenario, it was decided to simulate with different currents.

- **First scenario: Usual environment**

For the first scenario, the recreation of the typical environment along the Vilanova I La Geltrú coast was chosen. Utilizing the hydrodynamic simulation results, the 90th percentile of the maximum current velocity values was calculated for each direction. Subsequently, the average of these percentiles was determined to be 0.221 meters per second (equation 7). However, recognizing the necessity of evaluating the structure's stability under more extreme conditions, a maximum threshold of **0.3 meters per second in a 90º direction** was set.

By calculating the 90th percentile in each direction (northward, eastward, and upward), the varying flow patterns are accounted for and potential challenges from different directions are assessed. Taking the average of these percentiles provides a comprehensive representation of the overall hydrodynamic conditions the artificial reef may encounter.

The maximum threshold of 0.3 meters per second is set intentionally to encompass a range of more severe scenarios. By increasing the upper limit, the resilience and stability of the reef structure can be tested under more extreme hydrodynamic conditions, which are critical for its long-term performance and durability.

This approach strikes a balance between capturing potential challenges and ensuring a realistic and rigorous evaluation of the structure's stability. The increased threshold provides a margin of safety and allows for the assessment of the artificial reef's structural integrity and response to a broader range of hydrodynamic conditions

In summary, the 90th percentile calculations in each direction yielded an average value of 0.221 meters per second. However, to comprehensively evaluate the structure's stability and account for more extreme conditions, the maximum threshold of 0.3 meters per second was determined. This adjustment ensures the simulation covers a broader range of challenging scenarios, enabling informed decision-making and the design of a robust and resilient artificial reef structure capable of withstanding adverse hydrodynamic conditions.

Current data:

Speed (m/s)	Direction (deg)
0,3	90,0

Table 7: Current data for first scenario in OrcaFLex

- **Second scenario: Hurricane environment**

On the other hand, a second type of simulation was done to test the model in the worst situation possible. As evident from Table 7, the strongest current recorded, excluding the storm event in late 2019, is 0.545 m/s in the eastward direction. This measurement stands out as unusual and exceptional compared to the others. However, it was decided to round it up to 0.55 m/s and utilize this value for the hydrodynamic simulation.

The choice of using 0.55 m/s as the maximum current velocity (90º direction) for the simulation is based on several factors. Firstly, the intention is to incorporate a more rigorous and challenging scenario to assess the stability of the reef structure. By considering the strongest recorded current value, the simulated conditions encompass the most extreme hydrodynamic situations that the structure may encounter.

Additionally, rounding up the value to 0.55 m/s provides a margin of safety in the project assessment. It accounts for potential measurement errors or fluctuations in the current data while still representing a demanding condition that the structure needs to withstand.

While the 0.55 m/s value remains an extreme scenario, it is crucial to evaluate the reef's stability and performance under such conditions to ensure its long-term resilience. By subjecting the structure to more severe simulations, it is possible to gain confidence in its ability to withstand intense currents and make informed design decisions to enhance its stability.

In summary, rounding up the maximum recorded current velocity of 0.545 m/s to 0.55 m/s for the simulation allows for a more challenging and rigorous assessment. This decision is made to comprehensively evaluate the stability of the reef structure and ensure its resilience under extreme hydrodynamic conditions.

To conduct the simulations, a wave simulation was also added. Analysing different wave predictions of 2023, it could be seen than the waves do not exceed the meter high during this season. [14]

0-3 h	3-6 h	6-9 h	9-12 h	12-15 h	15-18 h	18-21 h	21-24 h
1' 5"	1' 7"	1' 6"	1' 6"	2' 0"	1' 9"	1' 5"	1' 1"
0.44 m	0.49 m	0.45 m	0.46 m	0.6 m	0.53 m	0.42 m	0.32 m
▲ S	▲ S	▲ S	▲ S	▲ S	▲ S	▲ S	▲ S
2	2	2	2	3	3	2	2

Table 8: Wave prediction for May, 23th of 2023

However, as for the possible international market that is aimed to reach and because of the geographical position of the model and the possibility of bigger waves on that area, it was decided to simulate a JONSWAP wave type. The JONSWAP (Joint North Sea Wave Project) spectra is an empirical relationship that defines the distribution of energy with frequency within the ocean.

The JONSWAP spectrum is effectively a fetch-limited version of the Pierson-Moskowitz spectrum, except that the wave spectrum is never fully developed and may continue to develop due to non-linear wave-wave interactions for a very long time. Therefore, in the JONSWAP spectrum, waves continue to grow with distance (or time), as specified by the α (alpha) term, and the peak in the spectrum is more pronounced, as specified by the γ (gamma) term [15]. This is particularly important as it leads to enhanced non-linear interactions. [16]

$$S(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left[-\beta \frac{\omega_p^4}{\omega^4}\right] \gamma^a \qquad (8)$$

The wave data and spectral parameters that have been used to direct the simulation can be seen on table 9.

Data for wave train: Wave1

Wave data:

Direction (deg)	Hs (m)	Tz (s)	Wave Origin X (m)	Wave Origin Y (m)	Wave Time origin (s)	Wave type	Number of wave directions
60,0	2,0	4,0	0,0	0,0	0,0	JONSWAP	1

Spectral parameters: Partially specified

γ	α	σ1	σ2	fm (Hz)	Tp (s)
50,0	0,02654	0,07	0,09	0,20434	4,89373

Components:

Seed	Number	Relative frequency range Minimum	Relative frequency range Maximum	Maximum component frequency range (Hz)
12345	200	0,5	10,0	0,05

Table 9: Wave data and spectral parameters

As displayed in the figure, the JONSWAP wave created, is a simulation of one direction 2 meters waves in a period of 4 seconds. These are applied in a direction of 60 degrees.

Another important parameter is the stiffness usually between the values of 7,792kN/m/m² and 779.2 kN/m/m², depending on the deepness of the area. To perform the simulation, a value between that range was established: **1400kN/m/m².** [17]

Finally, the duration time of the simulation was fixed at **300s**.

It is of importance to mention that different variations of each design were made during the process. For each of the designs, two different simulations where conducted; one initial simulation with only three layers as a structure and a second one with four layers. This was done so it was possible to analyse more precisely each of the models and their potential.

For this section, information such as the data obtained from the simulations and other explanatory graphs can be found in the appendices.

12.3.4 Model 1 ("Puzzle")

- **Three layers**

To undertake the study, it was necessary to first extract some data from SolidWorks in order to use it in OrcaFlex.

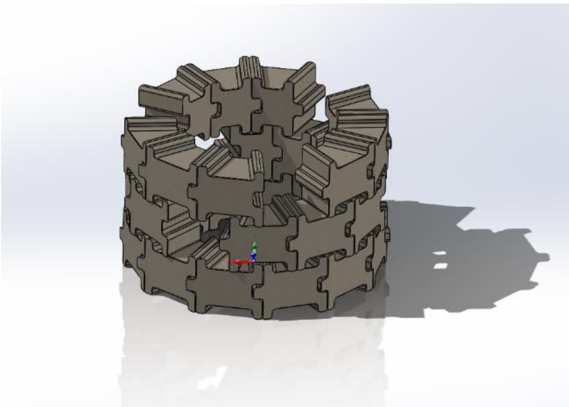


Figure 71: Model 1: three layers structure used for the simulation

- Mass = 322.368,96 grams
- Volume = 322.368.963,06 cubic millimetres
- Surface area = 11.086.681,41 square millimetres
- Center of mass: (millimetres)

  X = 0.00

  Y = 337.50

  Z = 0.00

- Exterior diameter (de) = 1.117,62 millimetres = 1,11762 meters
- Interior diameter (di) = 701,61 millimetres = 0,70162 meters
- Hight (h) = 716 millimetres = 0,716 meters

Previous calculations:

- Contact surface area (Ac):

$$Ac = \pi \cdot \left(\frac{de}{2}\right)^2 - \pi \cdot \left(\frac{di}{2}\right)^2 = \pi \cdot \left(\frac{1{,}11762}{2}\right)^2 - \pi \cdot \left(\frac{0{,}70162}{2}\right)^2 = 0{,}5943m^2$$

- Volume:

$$V = \pi \cdot \left(\frac{de}{2}\right)^2 \cdot h - \pi \cdot \left(\frac{di}{2}\right)^2 \cdot h = \pi \cdot \left(\frac{1{,}11762}{2}\right)^2 \cdot 0{,}716 - \pi \cdot \left(\frac{0{,}70162}{2}\right)^2 \cdot 0{,}716 =$$

$$= 0{,}425584m^3 = 425\ 584\ 919mm^3$$

- Mass:

$$m = \rho \cdot V$$

$$m = 0{,}0024 \cdot 425584919 = 1\ 021\ 403{,}806g$$

$$m \approx 1\ te$$

- **First scenario:**

Current of 0,3 m/s at 90º.

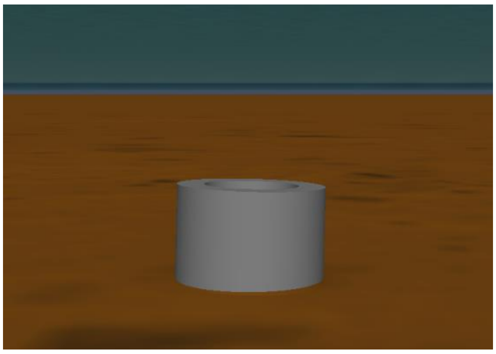


Figure 72: Model 1 "Puzzle" in OrcaFlex

- <u>Base Dynamic results (x,y, z):</u>

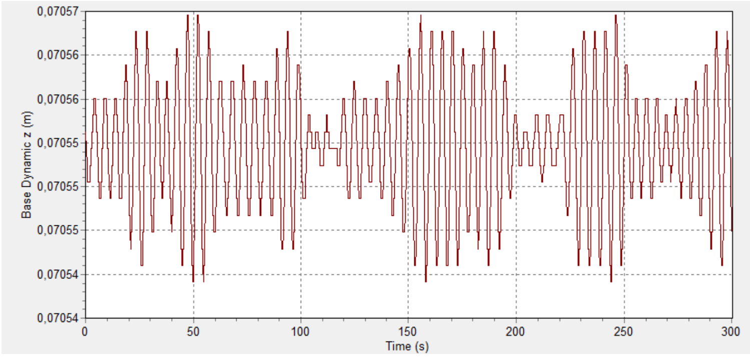


Figure 73: Graphic of base dynamic Model 1, 3 layers (axis Z). First scenario

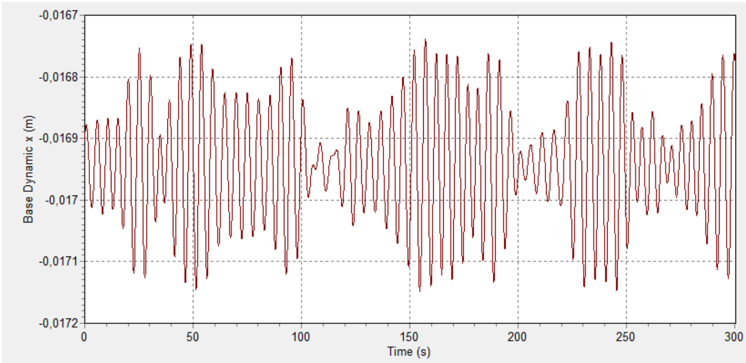


Figure 74: Graphic of base dynamic Model 1, 3 layers (axis X). First scenario

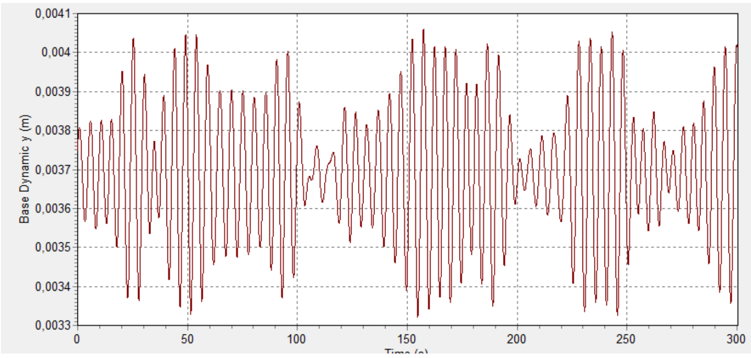


Figure 75: Graphic of base dynamic Model 1, 3 layers (axis Y). First scenario

As evidenced by the graphics obtained, the model presents an almost no noticeable displacement. By analysing the data, the highest value obtained is approximately 0,07 meters in the axis z, what ends up as an incredible result considering the dimensions and weight of the design. Because the highest value is on the vertical axis, it can be deduced that the main movement that the structure has is by sinking to the seabed, which may also contribute to stability in the other axes (this observation can also be done by observing the final position of the structure in figure 96). Nonetheless, this result is intriguing because in other areas, this outcome could improve if the stiffness of the zone is higher. This suggests that the model would resist the usual currents of the area and considerable waves if it was necessary.

- Base Rotation results (x,y, z):

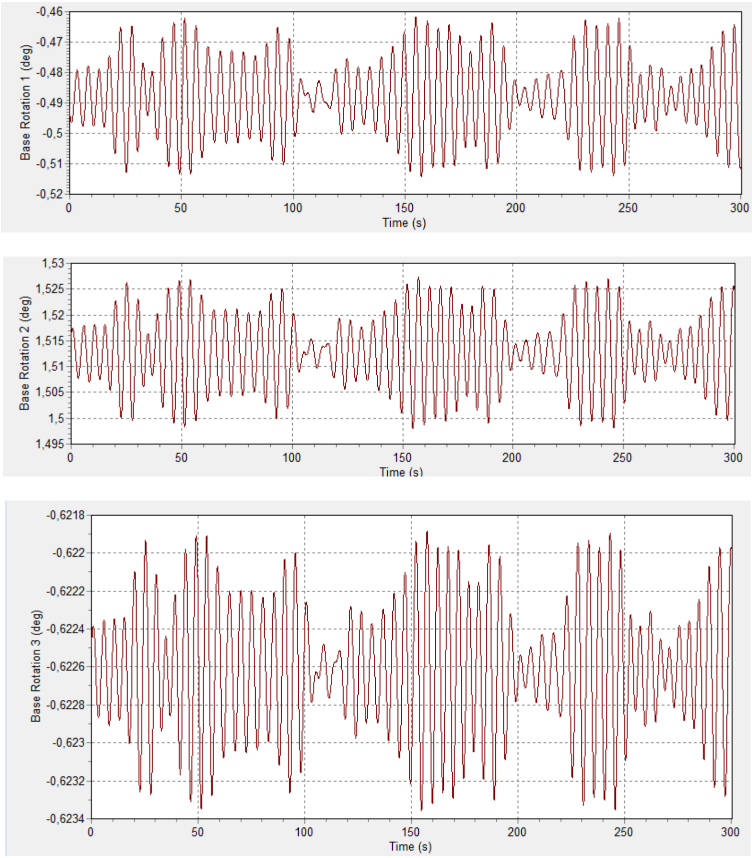


Figure 76: Graphs of base rotation Model 1, 3 layers (x,y,z). First scenario

In addition, by the study of the base rotation, it can be observed that the structure is almost in no movement, as the maximum angle of rotation obtained is of just 1,5 degrees approximately, what could be almost unnoticeable.

- **Second scenario:**

Current of 0,55 m/s at 90º.

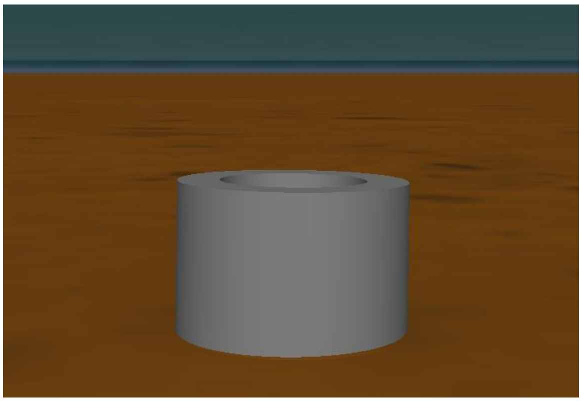


Figure 77: Model 1 "Puzzle" in OrcaFlex

- Base Dynamic results (x,y, z):

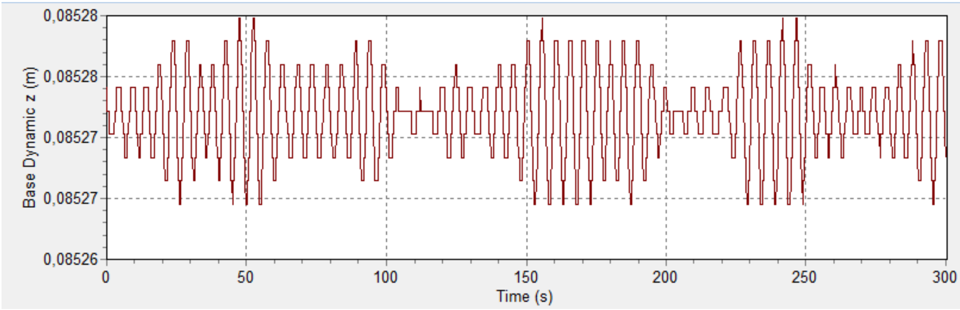


Figure 78: Graphic of base dynamic Model 1, 3 layers (axis Z). Second scenario

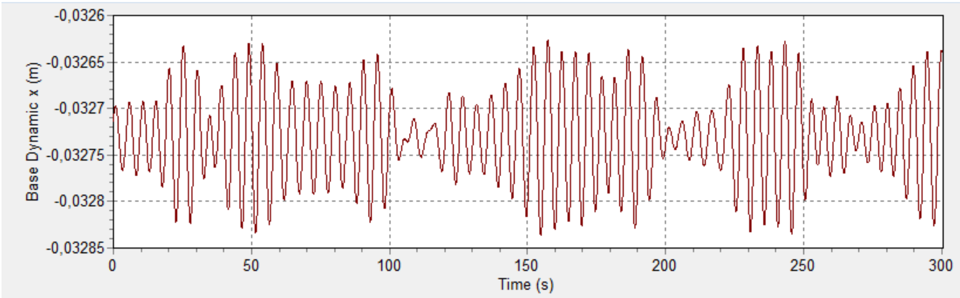


Figure 79: Graphic of base dynamic Model 1, 3 layers (axis X). Second scenario

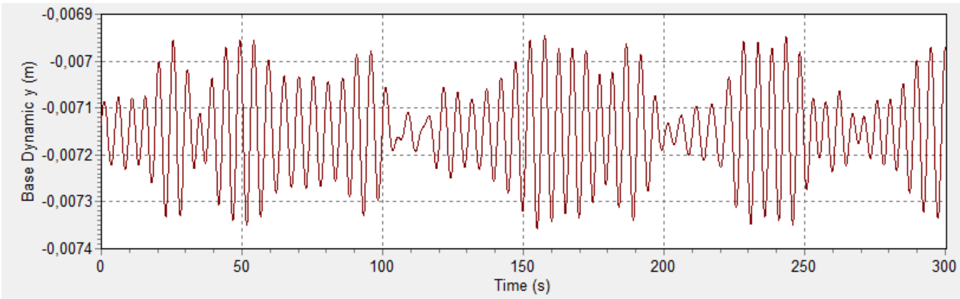
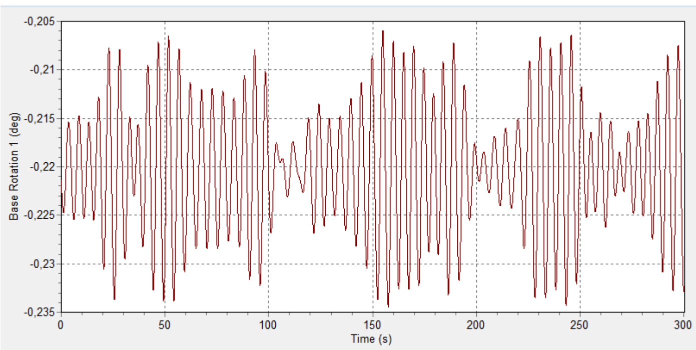


Figure 80: Graphic of base dynamic Model 1, 3 layers (axis Y). Second scenario

The results for these conditions, are also positive since the biggest value obtain is found in the axis z with a value of 0,08 meters, what obviously results as a higher value than on the previous one. However, as the displacement is considerable low, it can be said that the Model can withstand this currency as well.

- Base Rotation results (x,y, z):



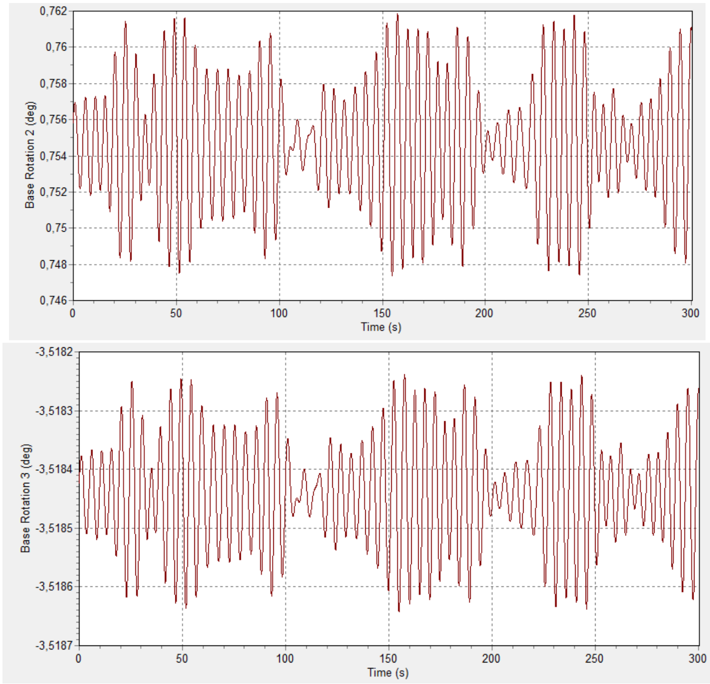


Figure 81: Graphs of base rotation Model 1, 3 layers (x,y,z). Second scenario.

On the other hand, the model suffers more rotation reaching a value of 3 degrees. This value is not worrisome as it makes almost no effect to the position.

- **Four layers**

This simulation is of great importance as it indicates whether the model can be taller (initial objective) and still withstand different currents and waves.

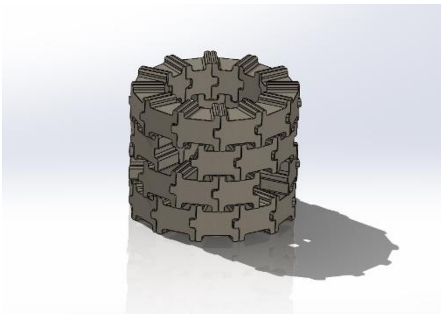


Figure 82: Model 1: four layers structure used for the simulation

- Mass = 451.316,55 grams
- Volume = 451.316.548,28 cubic millimetres
- Surface area = 15.521.353,97 square millimetres
- Center of mass: (millimetres)

  X = 0.00

  Y = 472.50

  Z = 0.00

- Exterior diameter (de) = 1.115,62 milimeters = 1,11562 meters
- Interior diameter (di) = 703,62 milimeters = 0,70362 meters
- Hight (h) = 926,21 milimeters = 0,92621 meters

- **Previous calculations:**
  - Contact surface area (Ac):

$$Ac = \pi \cdot \left(\frac{1{,}11562}{2}\right)^2 - \pi \cdot \left(\frac{0{,}70362}{2}\right)^2 = 0{,}5856m^2$$

  - Volume:

$$V = \pi \cdot \left(\frac{1{,}11562}{2}\right)^2 \cdot h - \pi \cdot \left(\frac{0{,}70362}{2}\right)^2 \cdot h = 0{,}6106m^3$$

$$V = 0{,}6106m^3 = 610600000mm^3$$

  - Mass:

$$m = \rho \cdot V$$

$$m = 0{,}0024 \cdot 610600000 = 1465400g$$

$$m \approx 1{,}46\ te$$

- **First scenario:**

Current of 0,3 m/s at 90º.

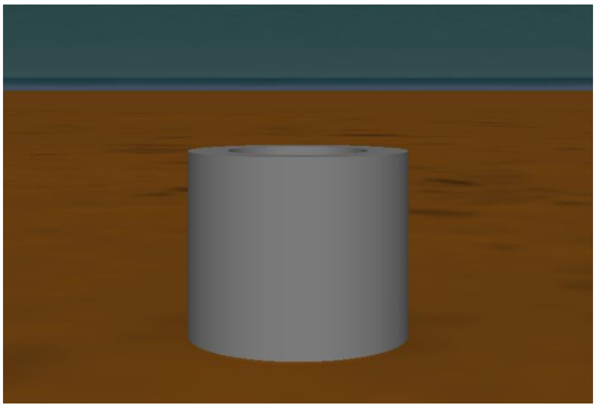


Figure 83: Model 1 "Puzzle" in OrcaFlex

- Base Dynamic results (x,y, z):

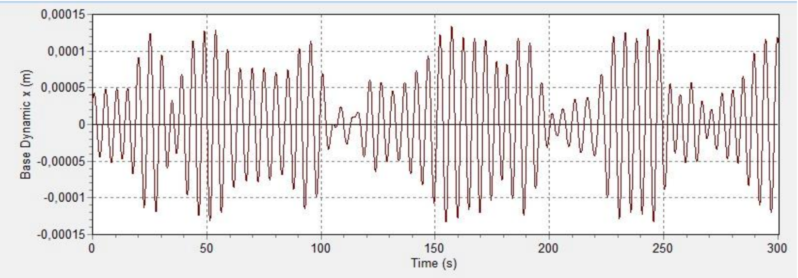


Figure 86: Graphic of base dynamic, Model 1, 4 layers (axis X). First scenario

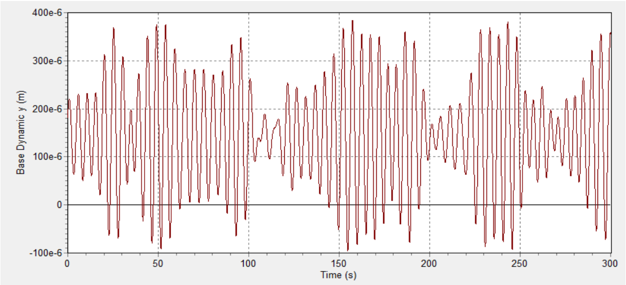


Figure 84: Graphic of base dynamic Model 1, 4 layers (axis Y). First scenario

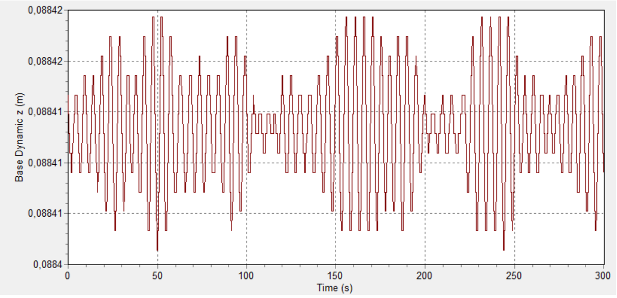
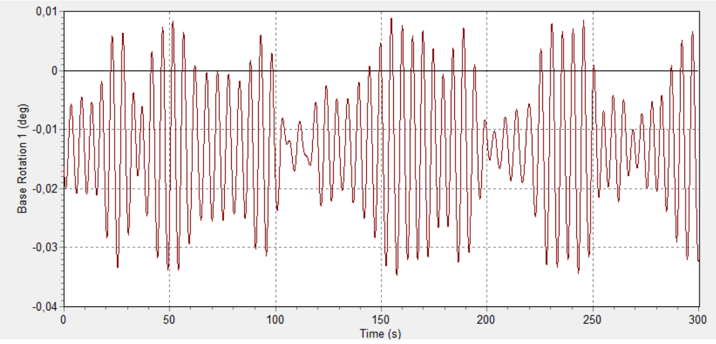


Figure 85: Graphic of base dynamic Model 1, 4 layers (axis Z). First scenario

After the simulations, judging by the graphics and data obtained, it can be shown that the model stands during this type of current, what would suggest that would have positive results on the usual environment of Vilanova I La Geltrú coast. Moreover, an almost unnoticeable movement can be appreciated, since on axis x and y the displacement is minimum. If the graphic that shown the axis z is analysed, it can be suggested that similar results to previous simulations are obtained.

- Base Rotation results (x,y, z):



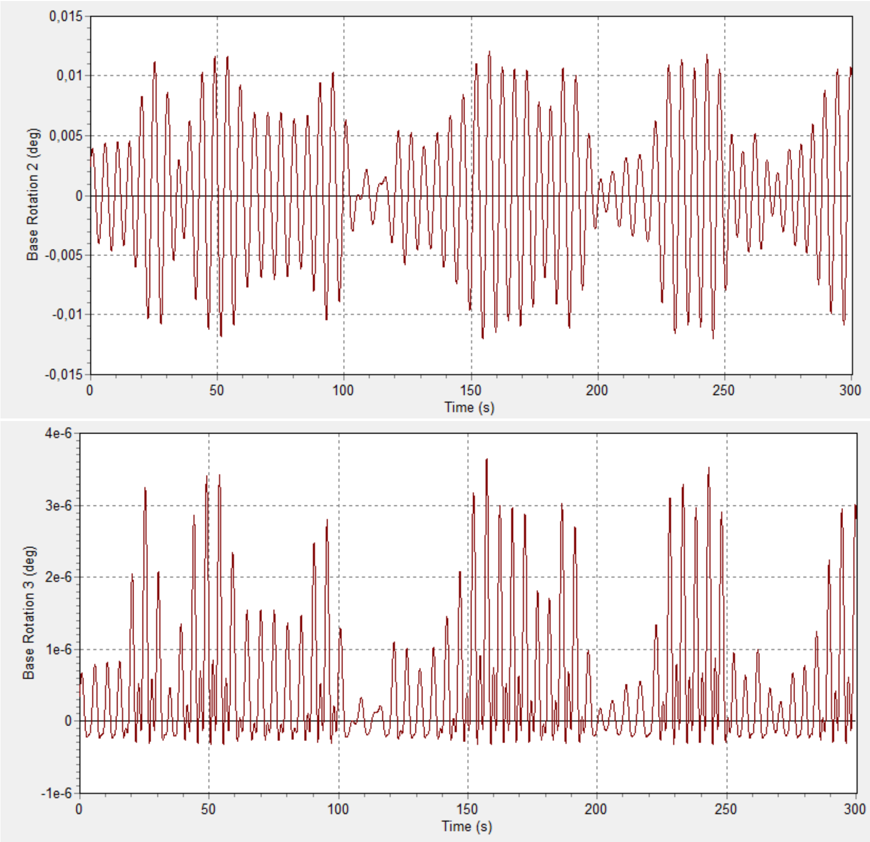


Figure 87: Graphs of base rotation Model 1, 4 layers (x,y,z). First scenario.

On the other hand, by analysing figure 108, the simulation results as an almost invariable value when it comes to the base rotation. Even though some spikes can be observed in the graphic, it can be appreciated that these values are not even one degree.

- **Second scenario:**

Current of 0,55 m/s at 90º.

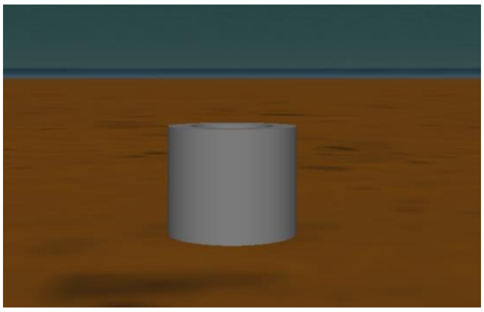


Figure 88: Model 1 "Puzzle" in OrcaFlex

- <u>Base Dynamic results (x,y, z):</u>

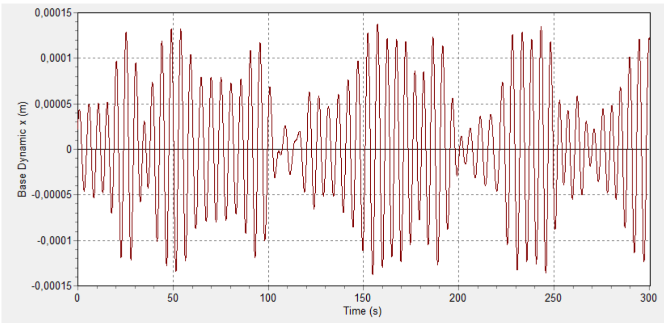


Figure 89: Graphic of base dynamic Model 1, 4 layers (axis X). Second scenario

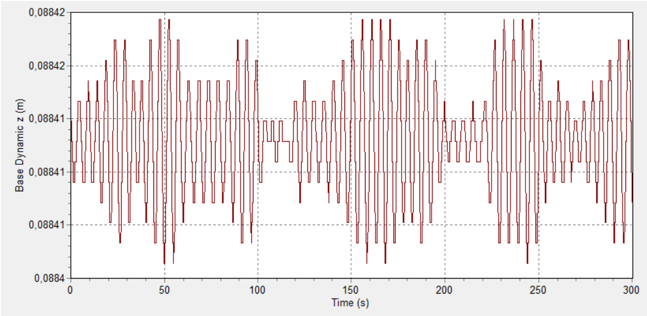


Figure 90: Graphic of base dynamic Model 1, 4 layers (axis Z). Second scenario

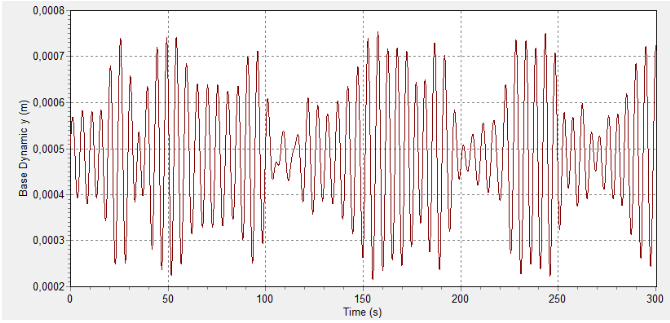
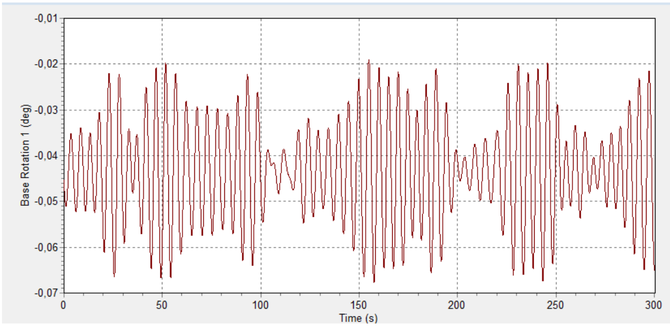
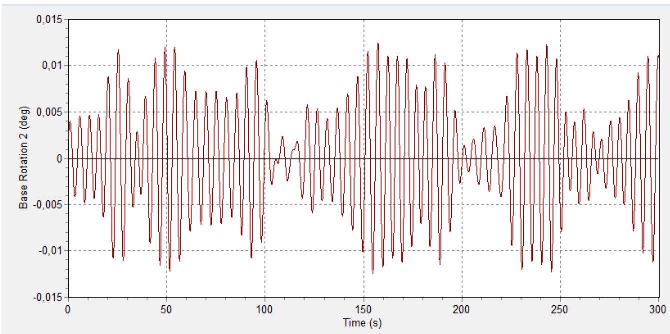


Figure 91: Graphic of base dynamic Model 1, 4 layers (axis Y). Second scenario

In this second scenario, some spikes reaching higher values can be observed. However, it can be said that these values are not worrisome as the design do not even move one meter when it comes to its position (axes x and y, figure 110 & 111) and suffers 0,08 meters sinking (figure 112).

- <u>Base Rotation results (x,y, z):</u>





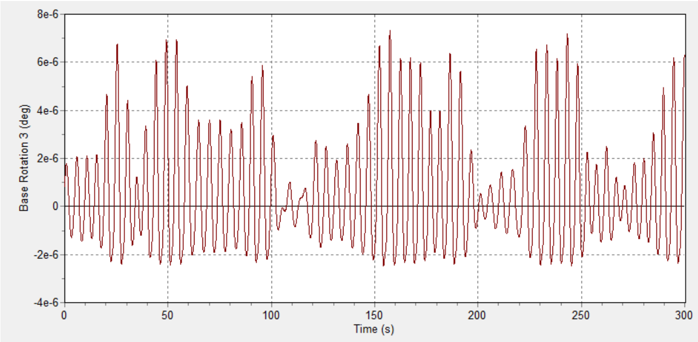


Figure 92: Graphs of base rotation Model 1, 4 layers (x,y,z). Second scenario.

These are amazing results as it concludes that four layers of the model could be installed and in addition, this design could even withstand critical currents. The sinking observed during the graphs is not concerning as it could be a result of the hardness of the seabed in that specific area. Based on the qualities determined for this design and simulation, it can be said that during the decision of the parameters for the simulation, a hard seabed was not established if this is compared to other areas where the design could also be placed. Additionally, information from the observatory has been obtained where different divers have reported the high hardness of the seabed in that area, which would yield even better results than those obtained. However, it would be essential to repeat the simulations for other seabed conditions as the non-sinking of the structure could result in increased displacement (in the x and y axes) due to reduced anchoring of the design.

12.3.3 Model 2 ("Lego")

- **Three layers**

As it has been stablished, it was decided to first simulate the design with a structure made up with three layers. By doing so, it is possible to provide more information to constructers and possible interested associations.

In order to begin with the study, it is necessary to extract different data from SolidWorks to use it in OrcaFlex.

- Mass = 780.847,30 grams
- Volume = 339.498.827,46 cubic millimetres
- Surface area = 10.614.316,89 square millimetres
- Center of mass: (millimetres)

X = 0.00
Y = 337.50
Z = 0.00

- Exterior diameter (de) = 1.129,62 millimetres = 1,129 meters
- Interior diameter (di) = 707,85 millimetres = 0,70785 meters
- Hight (h) = 703 millimetres = 0,703 meters

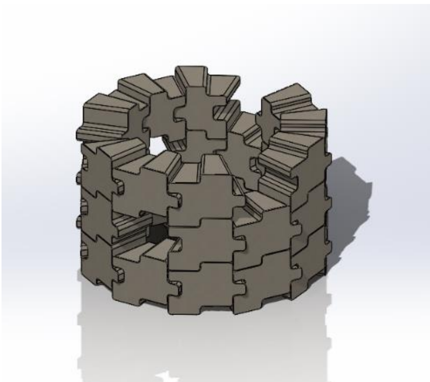


Figure 93: Lego structure

To perform the simulation, some parameters need to be recalculated. This is because the design is composed of different parts that contain various gaps between them. Therefore, for the simulation, a simplification of the structure is established, resulting in a single cylinder. This cylinder cannot possess the exact physical properties as the model created in SolidWorks due to the difference in volume. To address this, by applying the same center of mass and dimensions, the observed properties are recalculated. Previously mentioned parameters such as material density have been used. It is important to note that this procedure suggests that the actual design would be more effective. This is because the presence of gaps allows water to flow better within the structure, reducing the impact experienced during waves. This procedure has been performed for each of the simulations.

As for Model 1, the same procedure to obtain the real mass of the cylinder represented in the simulation was done.

Previous calculations:

- Contact surface area (Ac):

$$Ac = \pi \cdot \left(\frac{de}{2}\right)^2 - \pi \cdot \left(\frac{di}{2}\right)^2 (9)$$

$$Ac = \pi \cdot \left(\frac{1{,}129}{2}\right)^2 - \pi \cdot \left(\frac{0{,}70785}{2}\right)^2 = 0{,}6075m^2$$

- Volume:

$$V = \pi \cdot \left(\frac{de}{2}\right)^2 \cdot h - \pi \cdot \left(\frac{di}{2}\right)^2 \cdot hV = \pi \cdot \left(\frac{1{,}129}{2}\right)^2 \cdot 0{,}703 - \pi \cdot \left(\frac{0{,}70785}{2}\right)^2 \cdot 0{,}703 = 0{,}4271m^3$$

$$V = 427\ 125\ 700\ mm^3$$

- Mass:

$$\rho = 0{,}0024 \frac{g}{mm^3}$$

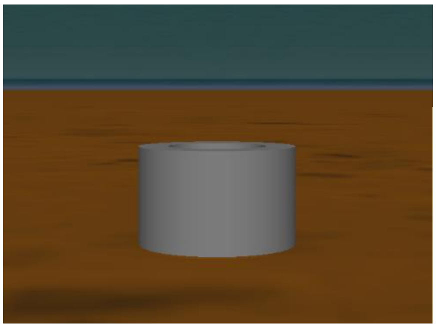
$$m = \rho \cdot V \ (10)$$

$$m = 0{,}0024 \cdot 427125700 = 1\ 025\ 101{,}68\ g$$

$$m \approx 1te$$

- **First scenario:**

Current of 0,3 m/s at 90º.



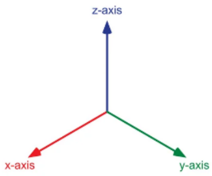


Figure 94: Model 2 "Lego" in OrcaFlex & Coordinate axis used by OrcaFlex

- Base Dynamic results (x,y, z):

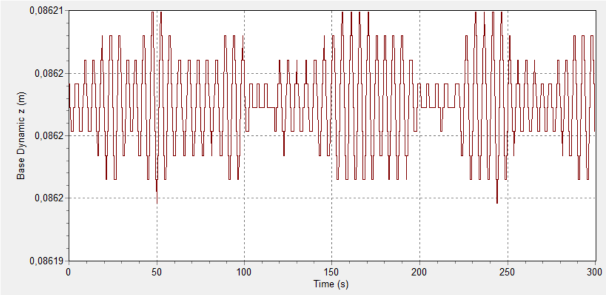


Figure 95: Graphic of base dynamic Model 2, 3 layers (axis Z). First scenario

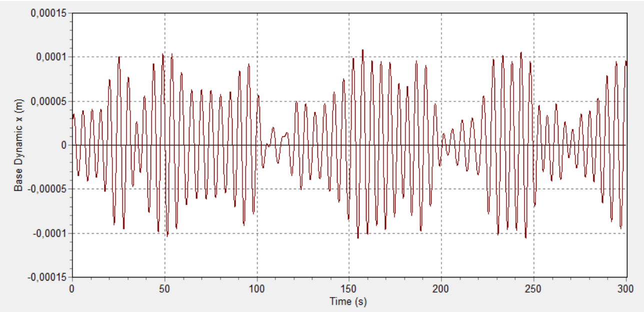


Figure 96: Graphic of base dynamic Model 2, 3 layers (axis X). First scenario

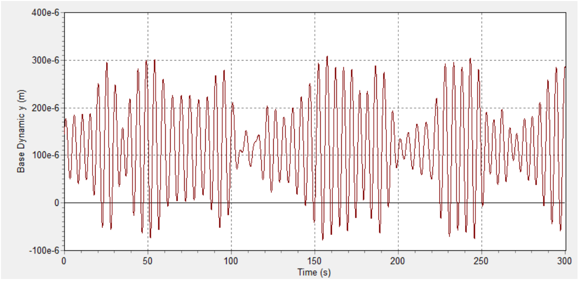


Figure 97: Graphic of base dynamic Model 2, 3 layers (axis Y). First scenario

As determined by the coordinate axis used in the program, different results can be obtained. Figures 73, 74 & 75 represent the displacement experienced by the model after the simulation. The x-axis and y-axis both correspond to the horizontal displacement of the structure, indicating if it will move from its position and by how much. In contrast, the z-axis corresponds to the vertical movement it undergoes. Therefore, this axis will indicate whether our model sinks into the seafloor or, conversely, if it lifts off the seafloor in a concerning manner due to the current.

Analysing the graphics, it can be observed that this first model structure does not move from its position on the seafloor, as the values obtained in the graph and simulation results do not reach even a millimetre of displacement. However, as mentioned before, it can be observed that our structure sinks. The fact that it only sinks by 0.08 meters (as shown in the Figure 75) is not concerning. However, further analysis is required to evaluate its behaviour when an additional layer is added to its structure. This may provide more stability to the structure but also reduce the usable area of the reef, as a portion of it would be submerged.

- Base Rotation results (x,y, z):

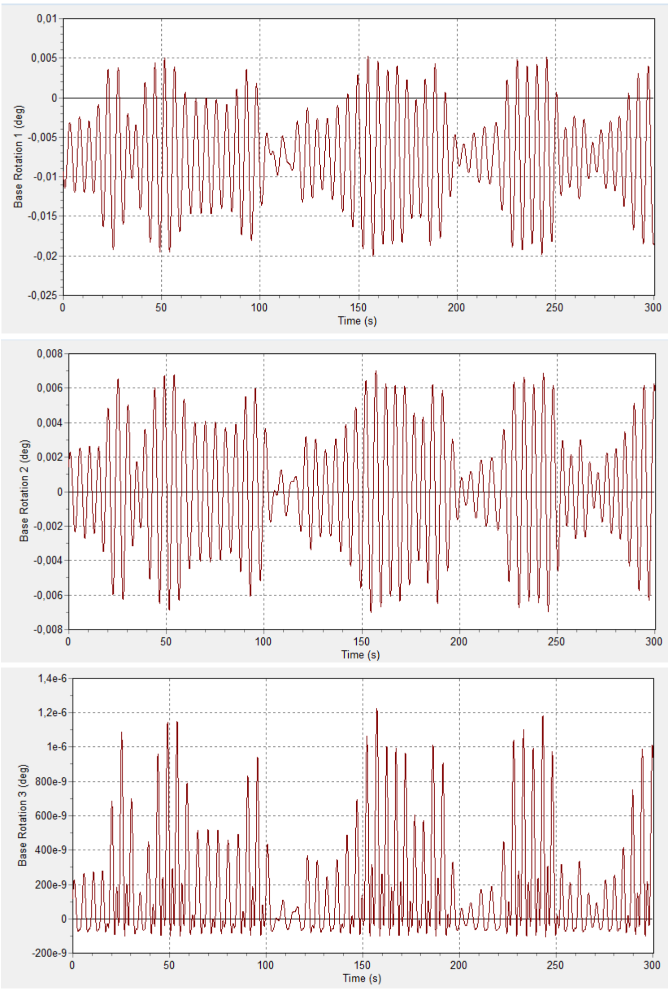


Figure 98: Graphs of base rotation Model 2, 3 layers (x,y,z). First scenario.

Another important parameter for analysis is the rotation of the model. This is significant because as it is composed of multiple pieces, if the structure undergoes significant rotation due to the current, there would be a higher likelihood of component dispersion and potential destruction of the structure. Analysing the graphs and values, it can be observed that the results are not centred around the axis, indicating that the rotation tends to occur more in one part of the model. However, these values are not of immediate concern as they are relatively low. As seen in the Figure 76, the values do not even reach 1 degree. It would be worrisome if these values reached 3 degrees or a magnitude that could make a significant difference.

- **Second scenario:**

Current of 0,55 m/s at 90º.

- Base Dynamic results (x, y, z):

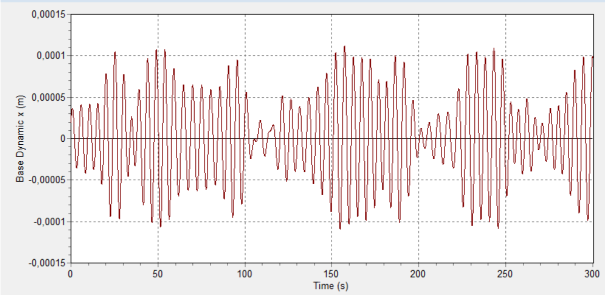


Figure 99: Graphic of base dynamic Model 2, 3 layers (axis X). Second scenario

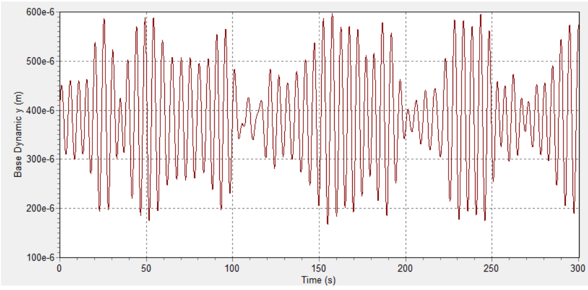


Figure 100: Graphic of base dynamic Model 2, 3 layers (axis Y). Second scenario

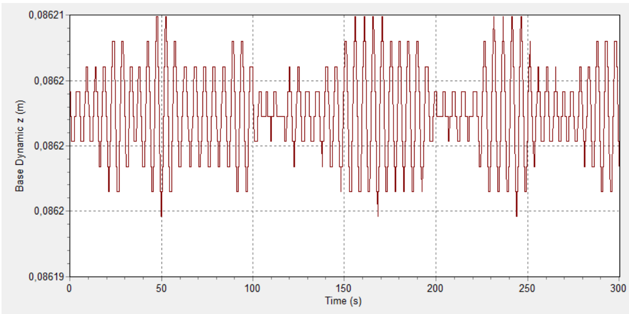


Figure 101: Graphic of base dynamic Model 2, 3 layers (axis Z). Second scenario

As mentioned earlier, in this next step, we can observe the effect of a higher current on our structure. Surprisingly, in terms of displacement, the model does not undergo significant changes, which is a good result. The values oscillate between very small numbers, which is not concerning. There are some peaks with higher values in the z-axis, but they have not increased considerably when compared to the graphs obtained with a lower current. By performing these simulations, it can be suggested that since the structure withstands these currents adequately, positive results are likely to be obtained when adding an additional layer as well.

- <u>Base Rotation results (x, y, z):</u>

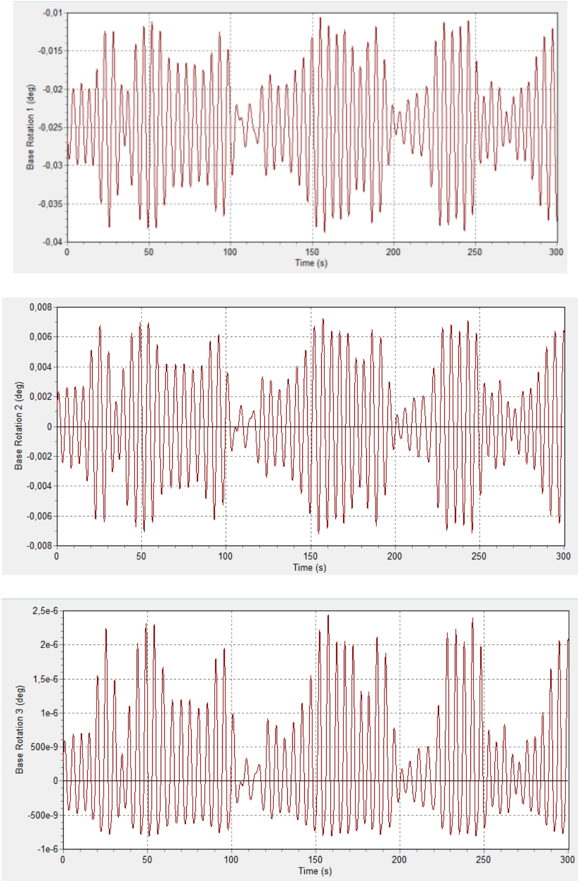


Figure 102: Graphs of base rotation Model 2, 3 layers (x,y,z). Second scenario.

- **Four layers:**

Next, we are going to test the model that was initially targeted to have four layers. These results are crucial as they will determine the feasibility of incorporating it into the seafloor.

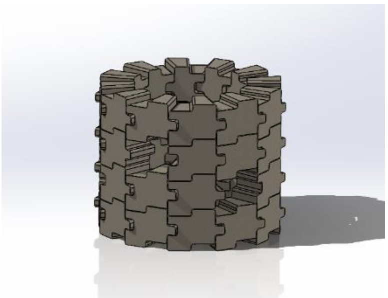


Figure 103: Model 2: four layers structure used for the simulation

- Mass = 1093186,22 grams
- Volume = 475298358,45 cubic millimetres
- Surface area = 14860043,64 square millimetres
- Centre of mass: (millimetres)

X = 0.00

Y = 472.50

Z = 0.00

- Exterior diameter (de) = 1.129,62 millimetres = 1,129 meters
- Interior diameter (di) = 707,85 millimetres = 0,70785 meters
- Hight (h) = 928 millimetres = 0,928 meters

Previous calculations:

- Contact surface area (Ac):

$$Ac = \pi \cdot \left(\frac{de}{2}\right)^2 - \pi \cdot \left(\frac{di}{2}\right)^2$$

$$Ac = \pi \cdot \left(\frac{1{,}129}{2}\right)^2 - \pi \cdot \left(\frac{0{,}70785}{2}\right)^2 = 0{,}607m^2$$

- Volume:

$$V = \pi \cdot \left(\frac{de}{2}\right)^2 \cdot h - \pi \cdot \left(\frac{di}{2}\right)^2 \cdot h$$

$$V = \pi \cdot \left(\frac{1{,}129}{2}\right)^2 \cdot 0{,}928 - \pi \cdot \left(\frac{0{,}70785}{2}\right)^2 \cdot 0{,}928 = 0{,}5638mm^3 = 563\ 830\ 227{,}6m^3$$

- Mass:

$$m = \rho \cdot V$$

$$m = 0{,}0024 \cdot 563830227{,}6 = 1\ 353\ 192{,}546g$$

$$m \approx 1{,}35te$$

- **First scenario:**

Current of 0,3 m/s at 90º.

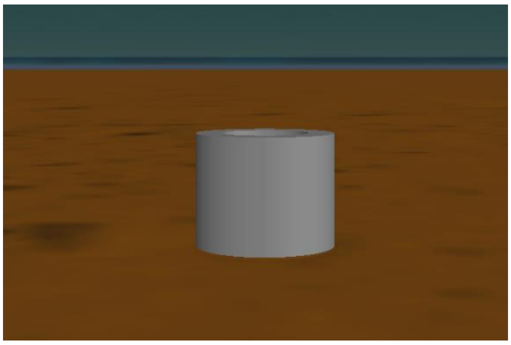


Figure 104: Model 2 "Lego" in OrcaFlex

- <u>Base Dynamic results (x, y, z):</u>

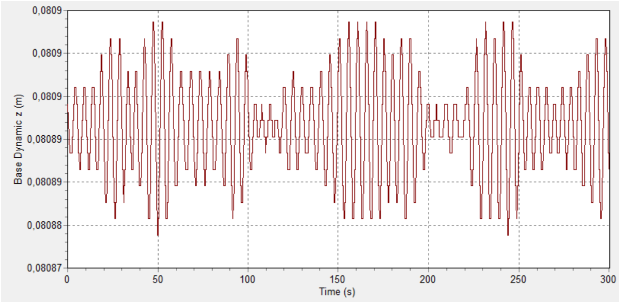


Figure 105: Graphic of base dynamic Model 2, 4 layers (axis Z). First scenario

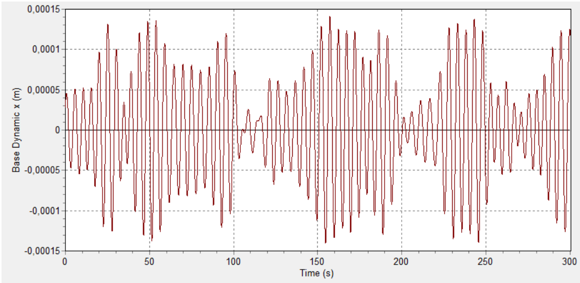


Figure 106: Graphic of base dynamic Model 2, 4 layers (axis X). First scenario

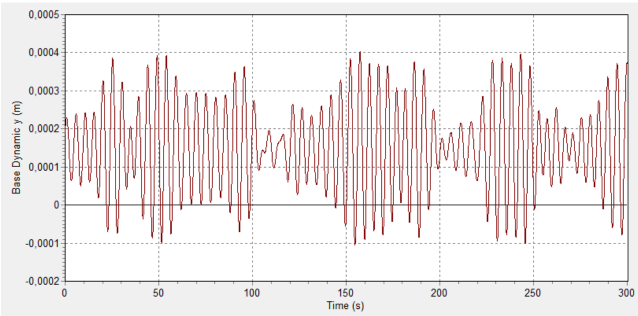


Figure 107: Graphic of base dynamic Model 2, 4 layers (axis Y). First scenario

- Base Rotation results (x, y, z):

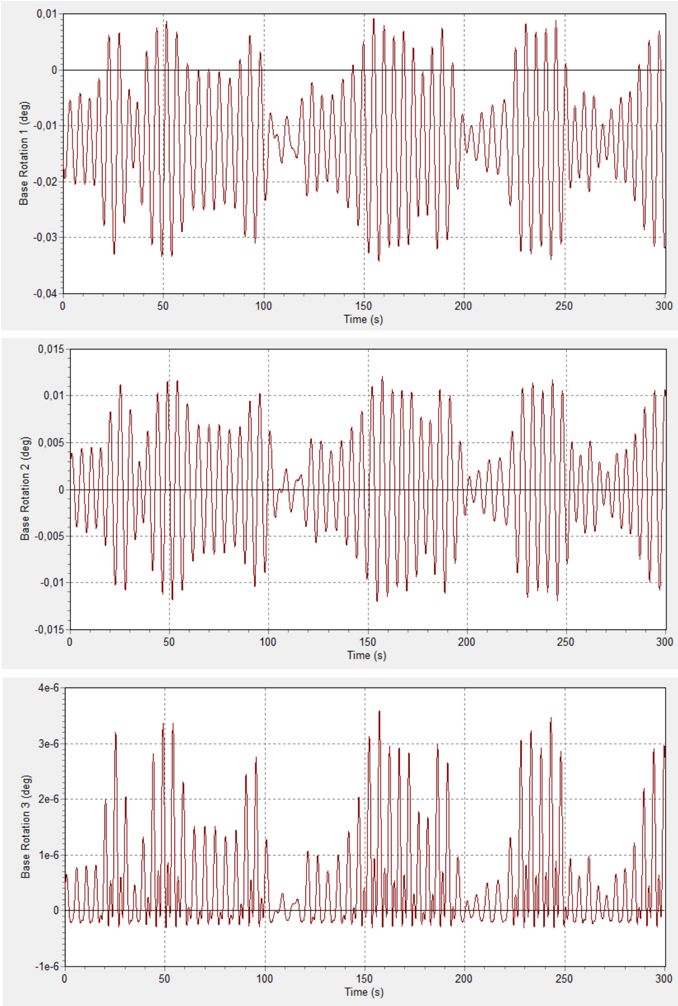


Figure 108: Graphs of base rotation Model 2, 4 layers (x, y, z). First scenario.

- **Second scenario:**

Current of 0,55 m/s at 90º.

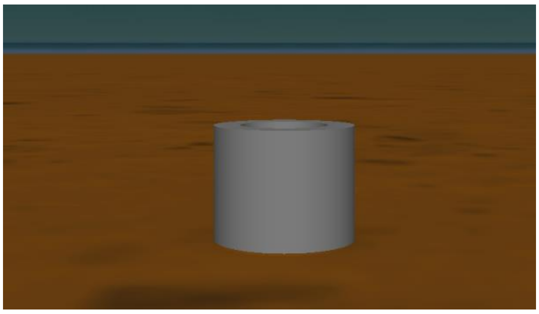


Figure 109: Model 2 "Lego" in OrcaFlex

- Base Dynamic results (x, y, z):

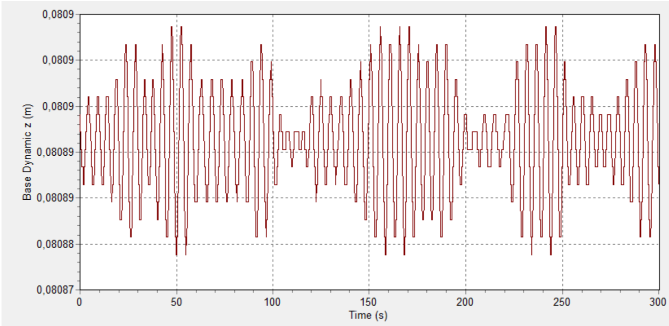


Figure 110: Graphic of base dynamic Model 2, 4 layers (axis Z). Second scenario

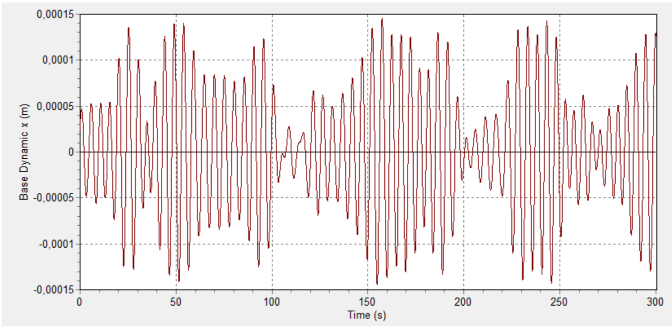


Figure 111: Graphic of base dynamic Model 2, 4 layers (axis X). Second scenario

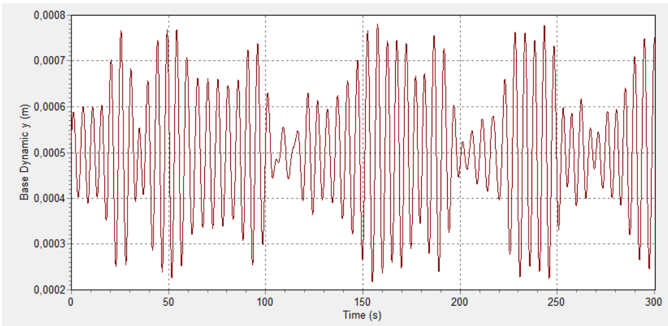


Figure 112: Graphic of base dynamic Model 2, 4 layers (axis Y). Second scenario

Surprisingly, even with the addition of one more layer, the results show minimal variation, and the same pattern as in the previous simulation persists, with the z-axis being the most affected. It is true that 0.08 meters is a significant value considering the dimensions of the model, but it is important to consider the hardness of the seafloor, which is very low in the simulations conducted.

- Base Rotation results (x, y, z):

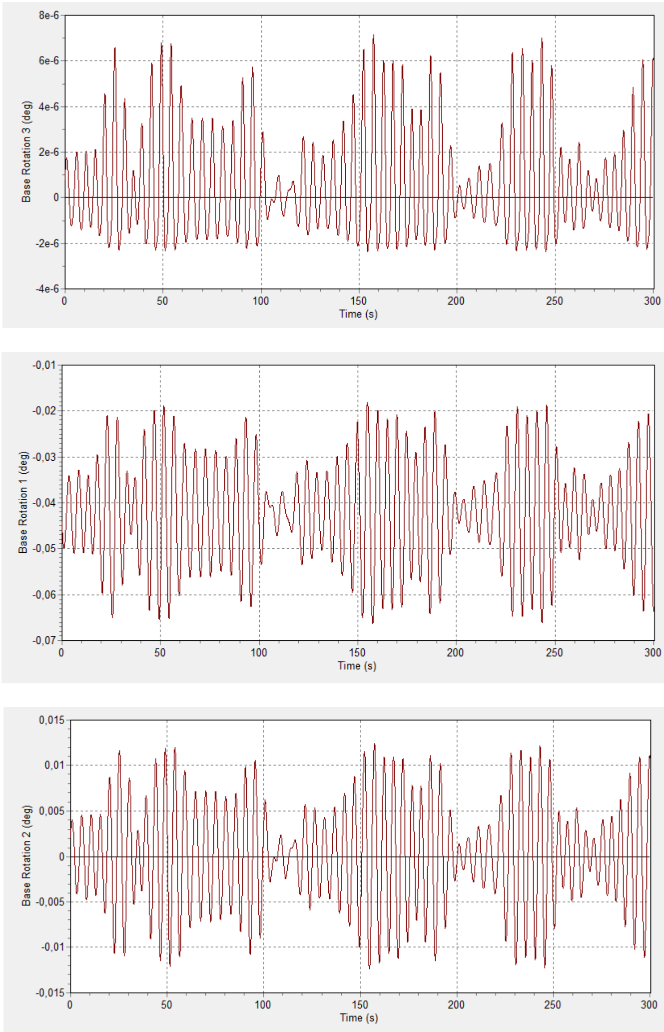


Figure 113: Graphs of base rotation Model 2, 4 layers (x, y, z). Second scenario

Regarding the rotation, we can observe that the model remains very stable. It can be concluded that these are highly positive values, indicating that this model would withstand critical conditions successfully.

Final simulation

Although during the project it was decided to create different scenarios in order to test the models that had been created, it was established to test the structures to the limit. To do so, several simulations were done until the point where the current provoked a noticeable displacement of the structure. This was done to both models using their 4 layers version. The results can be observed in the following pages.

- **Model 1 ("Puzzle"):**

For the first model, different values where tested when it comes to the current. Finally, by doing an analysis of the simulations, it could be observed that the design could stand until the value of current reached **2,2 m/s.** This suggest that this structure could be implemented in areas that do not have higher values. In figure 114 it can be seen the displacement that the model suffers because of the current.

Figure 114: Model 1, final simulation

- <u>Base Dynamic results (x,y, z):</u>

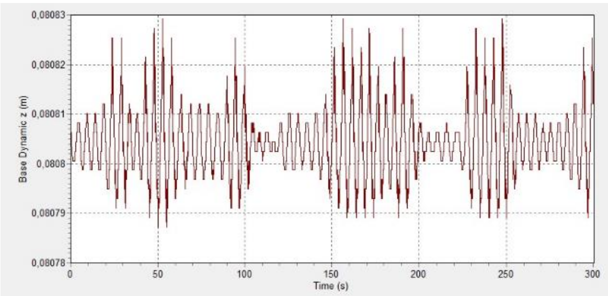


Figure 116: Graphic of base dynamic Model 1, 4 layers (axis z). Final simulation

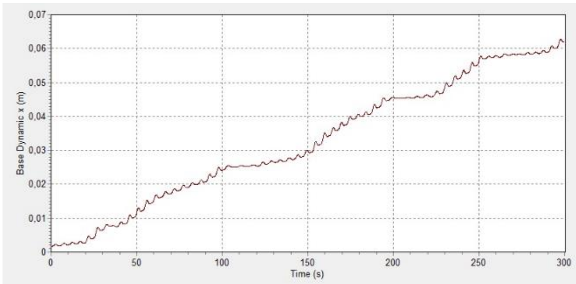


Figure 115: Graphic of base dynamic Model 1, 4 layers (axis x). Final simulation

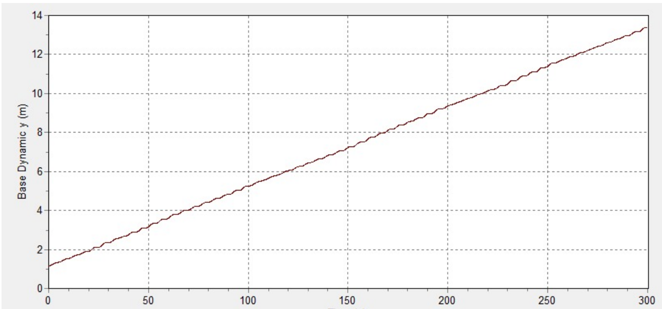


Figure 117: Graphic of base dynamic Model 1, 4 layers (axis Y). Final simulation

On the figures above, this last statement can be suggested: By the observation of figure 117, it can be seen that the model suffers a displacement of almost 14 meters during the 300 seconds of simulation. This is a negative result as the model is being placed in a protected area.

- Base Rotation results (x, y, z):

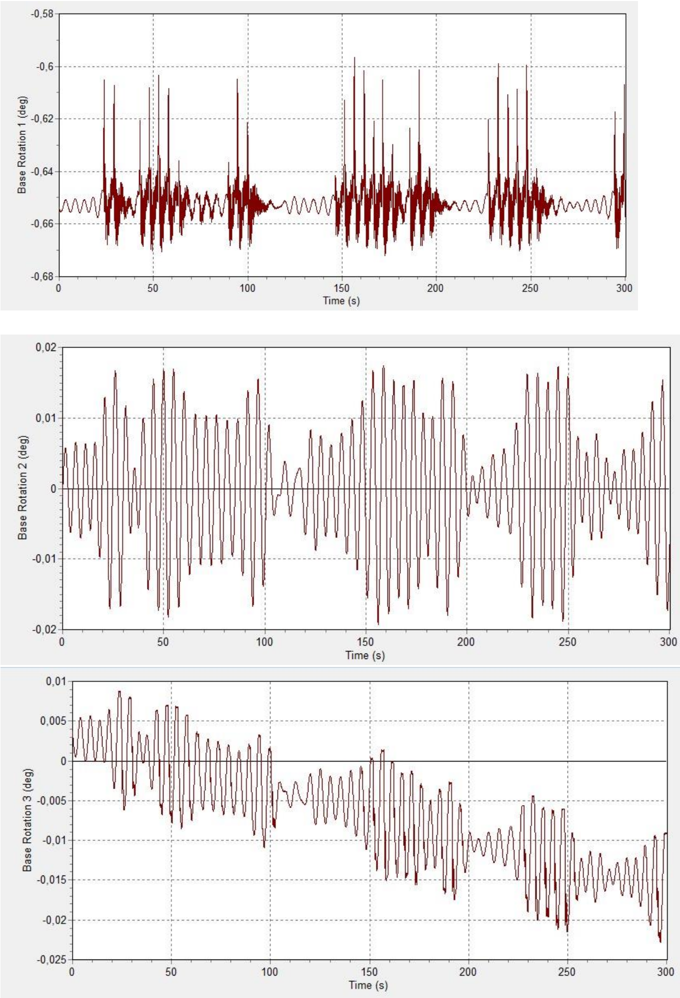


Figure 118: Graphs of base rotation Model 1, 4 layers (x, y, z). Final simulation

Moreover, it can be said that the model also rotates in a considerable way compared to the other simulations that have been made.

After this final simulation, as a conclusion, it can be said that this model can stand currents until **2,2 m/s.**

- **Model 2 ("Lego"):**

Different values of current were tested for the second model. After analysing the simulations, it was observed that the design remained stable until a current value of 1.7 m/s. This indicates that the structure could be implemented in areas where higher current values are not present. Figure 119 illustrates the displacement experienced by the model due to the current.

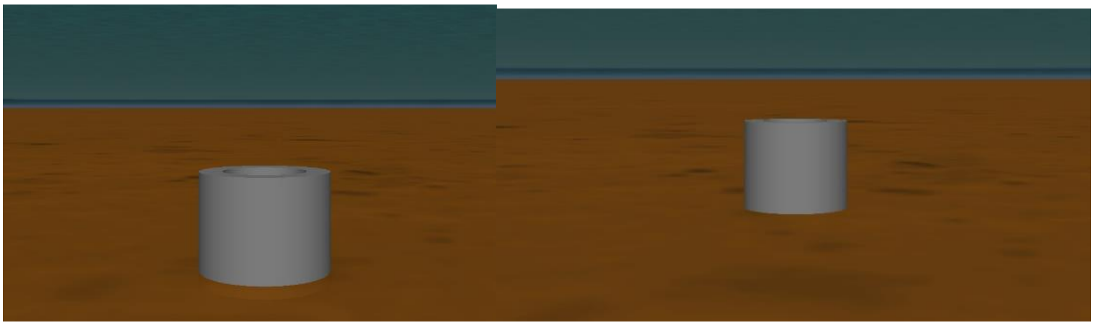


Figure 119: Model 2, final simulation

- <u>Base Dynamic results (x, y, z):</u>

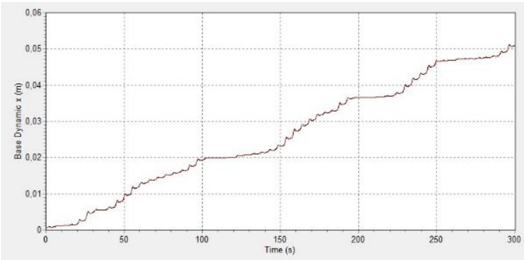


Figure 120: Graphic of base dynamic Model 2, 4 layers (axis x). Final simulation

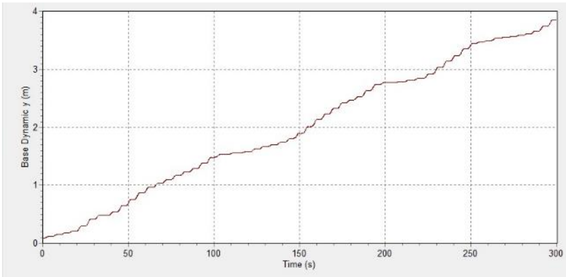


Figure 121: Graphic of base dynamic Model 2, 4 layers (axis Y). Final simulation

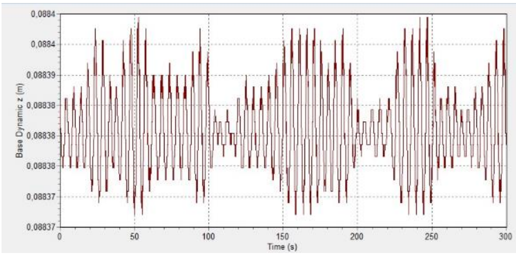


Figure 122: Graphic of base dynamic Model 2, 4 layers (axis Z). Final simulation

By looking at the graphics obtain on dynamic displacement, it can be observed that in this case, the model experiences a displacement of almost 4 meters during the 300 seconds that the simulation runs. Moreover, some movement is also experienced on axis x. On the other hand, it experiences the same results on axis z that it suffered on previous simulations.

- Base Rotation results (x, y, z):

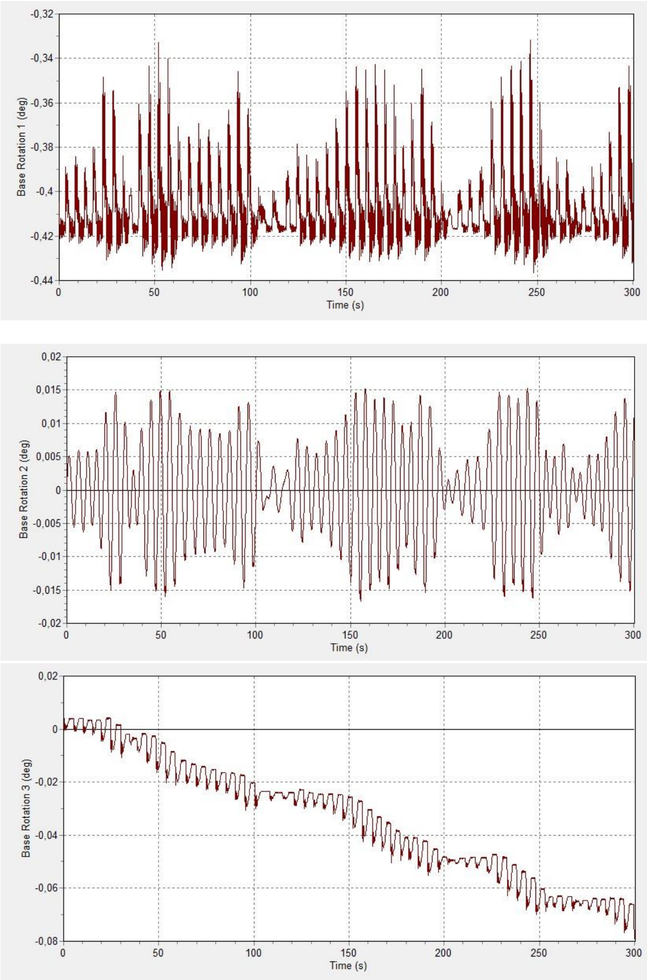


Figure 123: Graphs of base rotation Model 2, 4 layers (x, y, z). Final simulation

The model also rotates in different directions as can be seen in the figure 123I.

Taking everything into consideration, it can be said that this design can resist currencies until **1.7 m/s.**

Both designs can stand considerable currents compared with the ones that can be found in the coastline. This suggest that both models could be implemented in areas with higher current and waves values.

12.4 Achieved goals/requirements

After carrying out the simulations, it has been possible to obtain different conclusions which have contributed to the development of the project.

The main obstacle that the project faced was to ensure that the design would hold up on the seabed and withstand the currents created by the water. For this purpose, different simulations have been carried out with different compositions in its structure in order to create the most complete analysis possible. In addition, different scenarios have been carried out where the structure faced different values of current.

During the process, it can be observed that both designs are suitable for the area since very similar results are obtained. it can be seen that both designs suffer displacements in terms of their x-axis and y-axis, resulting in a barely noticeable displacement in terms of their initial position. It is necessary to emphasize that where they suffer the most movement is in terms of the z-axis. This would indicate that both designs sink to the seabed. Although our aim was to have the structure affect the bottom as little as possible, it is inevitable that due to the hardness of the bottom these will adhere. It must be said that this may have resulted in helping to avoid displacements in the other shafts, as it has acted as a fixation. In order for the implementation of the design to be possible in other areas, further simulations would have to be carried out to test how other types of hardness would be affected.

It is necessary to mention that for the simulations carried out, a cylinder without cavities or reliefs has been created. Because of this, they do not exactly replicate the real situation. Even so, there is a possibility that because the real design of our reef contains holes in its surface, this could help in terms of current flow and reduce the impact of the forces created by the water.

Finally, it can be concluded that the results obtained with the simulations suggest that both designs are successful.

12.5 Risk analysis

Over the course of project, a risk analysis was done to overcome the different situations that may appear during the realization of it. To do so, an Excel sheet to calculate the probability and impact of each case and risk.

In the following table, different causes of risk that could have an impact to the development of the project can be observed. Each of them has been given a number between one to teen depending on the probability and impact that they can have. To continue, a *Risk Score* has been obtained by the multiplication of the two parameters. In addition, a *Risk Owner* and a *Category* was given to each of the risks that could affect. Finally, to overcome each of the situations a *Risk of response* was discussed.

RISK ID	Description Cause -> Risk -> Impact	Probability (P) (1-10)	Impact (I) (1-10)	Risk Score (P * I)	Risk owner	Category (Schedule, Budget, Quality)	Risk of response
1	pH level of the material has to be near to the ocean's water one, but the material used with the actual printer is highest--> Fishes can't adapt to the environment --> wich my require to look for another material	2	10	20	Team	Quality	Add some additives that lower the pH of the concrete used
2	Because of the geometry of our design -> Not be able to print with the concrete printer -> Need to find new ways to print it or change the design	7	3	21	Team	Quality	Change the design in order to make it with concrete
3	After the hydrodynamic simulation will be carried out -> model not stable for the strongest currents -> Re-design or seek for other material	8	2	16	Team	Quality	Re-design or seek for material with other density (Add a slab at the [illegible]
4	Eventhough we are trying to do simulations as closest to reality as we can -> Risk of not being able to implement -> Future researches in order to improve the design	7	4	28	Team	Quality	Other researchers will need to re-analyse
5	Because of the reasearch of materials that is being done on UPC Terrassa -> To not have enough time to test the materials (samples will be tested on June) -> Further research on our project will be necessary	9	1	9	UPC Terrassa	Schedule	Further research on our projectwill be necessary
6	Because of the modular structure -> After printing the prototype the different component may not stick togheter -> Re-think the whole design	3	9	27	Team	Quality	Further research on our design will be required
Total risk score				121	MAX RISK	600	20,16666667

Table 10: Table of risks that can appear during the project

By doing this analysis, a total risk score of 121 was obtained, which by comparing them with the worse scenario (maximum risk of 600) resulted as a rating of **20,16%**.

To finalize the process, this rating was situated on the table showed below: this result has a **medium high** rating of risk.

RATING	1	2	3	4	5	6	7	8	9	10
	LOW		MEDIUM		MEDIUM - HIGH		HIGH		VERY HIGH	
	0-5%		5-10%		10-30%		30-50%		>50%	
CASE STUDY						x				

Table 11: Table rating the risk of our project

13. RESULT

In order to find the model that best suits the necessary requirements, different methodologies have been implemented and have provided different results.

To make the comparison of the three 3D models that where created, an AREIT index study was carried out, which allows the comparison of different artificial reef structures. It is necessary to add that for this process an excel spreadsheet has been created which can be used for future projects related to this same study, which helps in the realization of the calculations avoiding that these are done by hand. With this process, it was possible to obtain the following conclusion: the "Puzzle" design with four layers is the one that stands out the most among the three, but on the other hand, its same version with three layers is the one that gives the worst results. In addition, as expected, due to the surface area and other parameters, it is concluded that the four-layer design performs better than the three-layer design.

To further analyse the models, a 1:10 scale prototype of each of the three initial models was made. After this, the "Asymmetric" model was discarded due to the complexity of its construction and its poor stability, leaving the project with two models.

Regarding the price of each piece although the cost is similar, the “Puzzle” piece are 40 cents less expansive.

Finally, the simulations performed on the two remaining models ("Puzzle" and "Lego") suggest that both give positive and very similar results.

As a conclusion, it can be said that the "Puzzle" model is the best option if the objective is to create a structure that reaches the four layers. On the other hand, if the user wants to implement a model of only three layers, it would be advisable to use "Lego" because with the analysis of the AREIT index, it can be observed that it provides better results.

14. CONCLUSION

After the completion of the project, several conclusions and results have been drawn, which will be discussed below.

The Artificial Reefs project started with the study of the area where the design was going to be implemented. This has made possible the best adaptation and creation of the design since it has given the ability for the model to adapt and respect the natural environment in which it is located in the best way. In addition, after the analysis of the different species that inhabit the area, it has been possible to obtain different parameters which have been used later for the design. Some of them could be the dimensions that were required for the holes and the design itself. This has been vital due to the project's commitment to the environment and the team's respect for the species that inhabit the planet.

With the realization of the design, it has been possible to create two proposals with different modular structure. This made the project meet one of the main objectives that were established: the creation of a relatively light and easy-to-install model. This factor distinguishes this artificial reef from others that are already on the market, because by reducing the difficulty of installation, the price of the project is considerably reduced and therefore makes it much more implementable. This design also contributes to create a product with a long life cycle and therefore, as established, fulfill the idea of creating definitive and long-lasting solutions.

It is necessary to add that with the selection of materials and methodologies used, it has been possible to develop the project in the most ecological way possible.

In conclusion and as a summary, the project of the creation of an artificial reef with a 3D concrete printer, has achieved the objectives and expectations that had been determined at the beginning of the it and as a result has created two design options that contribute to the search for solutions that aim to restore marine diversity and therefore the salvation of our planet.

15. RECOMMENDATIONS

Although the team has tried to carry out a process to analyse and test the product as realistically as possible, there have been several factors that have contributed to the fact that the results may, in part, be relatively distant from reality.

Due to the approximation that has been made during the simulations, such as recreating the reef in a compact cylinder, this has not given results that are one hundred percent real. Also, it is necessary to mention that due to disasters or natural conditions it could be that the model does not comply 100% with the displacements and results obtained with the simulations.

Therefore, for the possible implementation of the model in other areas with different conditions, it is recommended to carry out static studies and simulations in order to test it. This is also recommended if in the future the creation of structures composed of five layers is required, which has not been analysed in this project.

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17. APPENDICES

17.1 Orientation on artificial reefs

[18] *Artificial Reefs: What works and what doesn't*

Artificial reefs are one of the many tools used by marine conservationists to restore coral reefs around the globe, they are made from a variety of natural or synthetic materials, and come in an infinite number of shapes and styles. The goal of these artificial reefs is generally to provide a stable growing area for corals, and habitat for fishes and all the other organisms that you would find on a natural reef. Over the years, artificial reefs have a lot of praise from those who have worked with them, but a lot of criticisms from scientists who see it as working on the symptoms and not the problems that face coral reefs. At the New Heaven Reef Conservation Program, they have been working with artificial reefs for over a decade, and in this chapter, let's look at some of the methods are found to be the most or least successful. [19]

What doesn't work

There are many factors that can make an artificial reef a success or failure, and even the same techniques and materials may work well in some situations and not in others. A complete description of the materials, techniques, and environmental factors to consider is a lot more than can fit in one article, which is part of the reason why we offer extended courses on the topic. However, below are some of the techniques we or others have tried that have failed, and a bit about why. Despite not working, we do see people repeating these same mistakes all the time while 'trying to reinvent the wheel,' so this is an important place to start.

1. Trash and potentially toxic materials

It should be a given, but we still see this going on today. Waste materials are rarely good for building reefs as they tend to be too small and not stable for organisms to grow on them. They often leach toxic chemicals or do not provide the surface micro-structure needed for organisms to latch onto. The most famous example of this is the Osborn reef built in Florida in the early 1970's, which saw around 2 million old tires dumped onto the sea bed. 30 years later, studies showed that almost no fish were living in the area, the tires were leaching toxic chemicals, and with each storm they were moving all over the sea bed (some were found washed ashore as far away as North Carolina).

Today's equivalent to these tire projects is probably best exemplified by those utilizing PVC or plastics. Throughout SE Asia, PVC pipe companies often sponsor these projects, contributing to their popularity. However, time and time again these so called artificial reefs are found to move or overturn in even light storms, break apart, and eventually start to degrade and release toxic chemicals. Furthermore, blue and green PVC has a smooth surface that corals will not readily recruit or attach to, and so it never ends up looking like a natural reef. Another example was a study by Dr. Laurie Raymundo in Guam following blast fishing, in which PVC mesh was laid out on the destroyed reef and transplanted with coral. Results looked promising at first, but at the 2010

APCRS Dr. Raymundo showed pictures of the area, no corals had attached and for the most part the mesh was making a mess of the area and was later removed.

2. Small/unsecured structures

The main goal of artificial reefs is to create solid structure, however that aim seems to get lost in some artificial reef projects. The classic example of this is using construction blocks (aka breeze or cinder blocks), which are literally designed to be lightweight and easy to break in half. Despite these attributes, the fact that they are cheap and readily available anywhere in the world has made them popular, albeit largely unsuccessful technique. Generally, these are utilized during very large government or corporate projects, using volunteers who drill holes in the blocks then epoxy coral fragments into the holes. Divers then place them in 'mats' on the reef or sand areas. They look great in the first few sets of pictures, but after the first small storm or monsoon season they generally can be found scattered across the reef edge or partially buried in sand, with few to none of the coral fragments still alive. There have been some very creative and elaborate attempts to lock up or create larger units out of the blocks using ropes or rebar, but the old axiom of 'garbage in, garbage out' usually holds true.

Although far from a comprehensive list, these are some of the most popular ways that folks unfortunately set themselves up for failure. But don't think failure is ubiquitous amongst artificial reef projects, because every year new and exciting techniques, materials, and designs are coming out that are proving their applicability.

So, What Does Work?

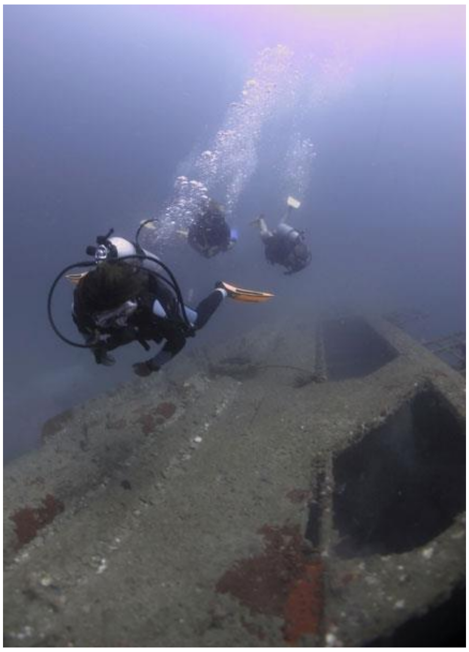
As you have probably gathered by now, an ideal artificial reef is:

- Stable in normal to large storms

- Made from long-lasting, solid, non-toxic materials
- Designed to have a high surface complexity (texture) for the recruitment of corals, sponges, and other organisms
- Designed to provide a high amount of structural complexity for fish and other animals
- Designed to either blend in with the natural reef, or be designed to stand out and convey a message (sculptures and art)

Again, considerations such as depth, placement, boat navigation, etc. are not discussed here, but are vitally important to success. Below we will look at some examples of artificial reefs we commonly work with and comment a bit on why we like these techniques, even if they might not fulfill all 5 of the criteria above.

1. Wrecks and other large steel structures



Metal ship wrecks are some of the oldest and most well developed artificial reefs, even if there resting location was not planned. Warships from World War I and II provide some of the most stunning examples of how the ocean can claim man-made structures and create a living ecosystem out of a foreign object. In some cases, old wrecks are so covered in corals and marine life that they have only been identified through advanced technologies such as LIDAR, or by accident during drilling or dredging operations.

Coral reef organisms grow well on steel structures, despite the concerns of some that iron and other limiting nutrients will favor algal or bacterial growth. Although utilizing materials of opportunity, purposefully sunk wrecks do however require environmental and safety preparations before being deployed. In addition to wrecks, but along the same lines, are the use of decommissioned oil platforms as artificial reefs, providing that proper environmental preparations are completed first, these structures can provide amazing 'islands of biodiversity' in otherwise barren seascapes.

It should be noted however that using mixed metal alloys is much less effective than steel structures. Due to the effects of electrolytic degradation that occurs between different metals when placed in a salt water solution, items such as cars, helicopters, or airplanes will degrade and break apart in only a few short months.

2. Concrete structures

Concrete is the favorite material to use for most reef managers for many reasons. First, it is a material that is very close in composition to natural coral limestone, and also it is strong, heavy, cheap, and readily available all over the world. Concrete can be made into nearly any shape or size, and lasts a long time under the ocean. Some critics claim that trace metals found in concrete (aka Portland cement) will cause coral disease, but this is never realized in the ocean, and in our experience, corals thrive on these structures.

The main drawback to using concrete is that structures can quickly become too heavy to deploy using the limited resources that most small reef managers have available. Some of our largest concrete projects (i.e. Buoyancy World, Mini Square, the DMCR Cubes, etc.) have only been possible because of partnerships with the government, which has allowed us access to large barges.

3. Modular units made of Steel rebar, Cement, or glass

Some of our favorite structures are smaller units that are easily deployed (light enough to be carried to a boat by volunteers) and then assembled into larger structures underwater. Suan Olan is one of our best examples of this, were we have some structures made out of prefabricated concrete parts assembled into interesting and sometimes interactive structures. We also have many of our Bottle Units there, which has been one of our most successful techniques to date. The units consist of a concrete base, into which glass bottles are placed and become the securement point for corals. The units are sunk into the sands to prevent them from moving around. Lastly, we have there many of our metal structures that are made from rebar. Providing these structures are kept small, rigid, and properly welded then they do really well. They provide an easy place to attach corals, tend to allow waves to pass through them to prevent overturning, and last about 8-10 years underwater. Once they do collapse, they are usually so covered in coral that things just keep growing as normal.

4. Mineral Accretion devices

Probably the most exciting method of artificial reef construction is the use of mineral accretion devices, or electrified artificial reefs (traditionally known as Biorock™). These start off just like our modular metal structures made of rebar, but once in the water low voltage electricity is passed through the structure. This creates an effect known as electrolysis, which provides cathodic protection to the structure (prevents it from rusting or corroding), and furthermore causes minerals from the sea water to precipitate out and collect on the metal. This action creates a beneficial environment for the growth of corals and other calcium carbonate secreting organisms, which tend to grow much faster on these structures (up tp 3-5 times) and survive better through disturbances such as temperature induced bleaching. Traditionally, these units have been very expensive and required a high amount of maintenance and expertise. However, we are working together with our partner CoralAid to modernize and revolutionize this technology so that more reef managers can utilize it.

Over the last few years, more and more interesting or novel methods materials are being designed, some of which show a lot of promise. These include the use of 3-D printers to create structures with exponentially greater surface and structural diversity that could be achieved through traditional means, and the increasing use of art and sculpture to draw more awareness to the plights of the ocean. For years, artificial reefs have been seen as mis-directed efforts or 'mindless meddling.' And there are many examples of where folks have gone for the attractive and media savvy route of building artificial reefs without focusing on actually solving the problems in their area. Such efforts will always end up in failure. However, more and more data and anecdotal evidence is showing that artificial reefs can and should be a part of an integrative and holistic reef management program.

[20] **Electrified Artificial Reefs**

An electric reef (also electrified reef) is an artificial reef made from biorock, being limestone that forms rapidly in seawater on a metal structure from dissolved minerals in the presence of a small electric current. The first reefs of this type were created by Wolf Hilbertz and Thomas J. Goreau in the 1980s. By 2011 there were examples in over 20 countries.

Construction process

The base of an electrified reef is a welded electrically conductive frame, often made from construction grade rebar or wire mesh which submerged and attached to the seafloor to which an electrical field applied. The frame (cathode) and a much smaller metal plate (anode) placed at a suitable distance from the frame initiates the electrolytic reaction.

Dissolved calcium carbonate and magnesium hydroxide and other minerals naturally found in seawater breakdown in the vicinity of the anode and recombine and precipitate out of the water onto the cathode. The exact composition of the minerals within the crystal formation is depends on their abundance, the climatic conditions and the voltage used. The structure which takes on a whitish appearance within days.

This electric field, together with shade and protection offered by the metal/limestone frame soon attracts colonizing marine life, including fish, crabs, clams, octopus, lobster and sea urchins. Once the structure is in place and minerals begin to coat the surface divers transplant coral fragments from other reefs to the frame which soon bond to the newly accreted mineral substrate.

Because of the availability of evolved oxygen at the cathode and the electrochemically facilitated accretion of dissolved ions such as bicarbonate, they start to grow, some three to five times faster than normal and soon the reef takes on the appearance and utility of a natural reef ecosystem.

As shore protection

Shorelines are increasingly susceptible to beach erosion and loss due to climate change which is resulting in rising sea levels and increasingly frequent and more powerful storms. Large structures such as breakwaters constructed to reflect waves to prevent erosion are problematic and can in fact contribute to further beach erosion since for force of waves is doubled due to the reversal of the wave direction vector with the reflected wave carrying sand from the structure's base back out to sea resulting in the structure failing over time.

Common electrified reef used for shore protection mimic the effect of a natural reef which prevent erosion by dissipating wave energy and causing waves to break before they impact the shore. In nature, large reefs, have been shown to dissipate up to 97% of their energy. They are based around the same open mesh frameworks as those used for coral restoration. Skeletons of dead coral and algae from the reef are then deposited and help grow beaches. Because these reefs mimic the properties of natural reefs they solve some of the challenges they have in storm dissipation and their self-healing qualities helps structures survive extreme storms as long as the electricity supply remains in operation.

In Turks and Caicos trials of electrified reefs of coastal protection survived the two worst hurricanes in the history of the islands, which occurred three days apart and damaged or destroyed 80% of the buildings on the island. Sand was observed to build up around the bases of the reef structure. In Maldives in 1997, shore protection reefs helped save several buildings, including a hotel, that had risked washing away due to severe beach erosion. The 50-meter-long shore protection reef stabilized and ultimately reversed erosion in several years, even allowing the beach to survive a tsunami in 2004.

[21] **Effectiveness**

Electrolysis of electric reefs enhances coral growth, reproduction and ability to resist environmental stress. Coral species typically found on healthy reefs gain a major advantage over the weedy organisms that often overgrow them on stressed reefs.

Biorock can enable coral growth and regrowth even in the presence of environmental stress such as rising ocean temperatures, diseases, and nutrient, sediment, and other types of pollution. Biorock represents the only known method that can sustain and grow natural coral species using only basic conducting elements, typically of a common metal such as steel. The process accelerated growth on coral reefs by as much as fivefold and restoration of physical damage by as much as 20 times. and the rate of growth can be varied by altering the amount of current flowing into the structure.

In one study, Porites colonies with and without an electric field were compared for 6 months after which time the current to the electric reef was eliminated. Growth differences were significant only during the first 4 months with longitudinal growth being relatively high in the presence of the field. The treatment corals survived at a higher rate.

On Vabbinfaru island in the Maldives, a 12-meter, 2 ton steel cage called the Lotus was secured on the sea floor. As of 2012, coral was so abundant on the structure that the cage is difficult to discern. The 1998 El Nino killed 98% of the reef around Vabbinfaru. Abdul Azeez, who led the Vabbinfaru project, said coral growth on the structure is up to five times that of elsewhere. A smaller prototype device was in place during the 1998 warming event and more than 80% of its corals survived, compared to just 2% elsewhere. However, power is no longer supplied to the project, leaving it vulnerable to the next round of bleaching. A study conducted in the Bahamas in 2015 showed that the electric field deterred sharks, specifically the bull shark and the Caribbean reef shark, from swimming and feeding in the area. The electric field is believed to affect sharks because of their electroreception abilities, however species with similar capabilities such as the bar jack and Bermuda chub did not appear to be affected by the electric field.

17.2 Analysing Article: Proposed Conceptual Framework to Design AR's

[13] Ars (Artificial reefs) are understood as man-made structures specifically designed and manufactured to fulfil at least one of the functions performed by natural reefs.

ARs are:

- usually modular structures with holes
- with concrete being the most common material employed in their construction (also the one considered in this study).
- In particular, 'green' concretes have been proposed in previous works

Overfishing and pollution have led to a marine habitat degradation, endangering the exploitation of its resources. The need to enhance marine ecosystems while halting the decline in fish stocks and boosting artisanal fishing is evident.

Marine ecosystems are habitats that support marine life. Marine life depends in some way on the saltwater that is in the sea (the term marine comes from the Latin mare, meaning sea or ocean). A habitat is an ecological or environmental area inhabited by one or more living species.

the installation of ARs has emerged as **(1)** a promising option for both providing habitat for marine species and **(2)** promoting sustainable fisheries. **(3)** ARs can also provide alternative ecosystem services, since they also attract recreational divers.

hard substrata are notably superior to soft ones in terms of productivity, diversity and the abundance of living organisms. It is a proven fact that some marine structures, such as jetties and oil platforms, function as natural reefs generating high densities of aggregating fish in shallow coastal areas and deep waters, respectively.

The performance of artificial reefs was traditionally assessed through population and community ecology through approaches based on experimental and field observations to quantify fish density, biomass or composition, among other indicators linked to the species of interest.

Now there is more need to design Ars for:

- Adopting an ecosystem ecology perspective which enables identification of the factors that limit the net primary production of a particular ecosystem.

  Once this has been done, the design of the ARs can be aimed at increasing NPP and nutrient cycling. In this way, it will be possible to determine the extent to which the ARs can contribute to enhancing a specific ecosystem before their installation.

- In most ecosystems, linked to **Net Primary Production** and how energy and biomass pass through the different trophic levels.

  Consequently, by adopting an EE perspective in the design of ARs, it will also be possible to estimate the impact they can have on secondary productivity.

Net primary production (NPP) is the amount of biomass or carbon produced by primary producers per unit area and time, obtained by subtracting plant respiratory costs (Rp) from gross primary productivity (GPP) or total photosynthesis.

NPP(net primary production) at all trophic levels depends mainly on three factors:

1. substratum availability
2. nutrient availability
3. light penetration

(the relative importance of each of these factors varies from one ecosystem to another.)

So the design and installation of ARs must ensure new autotrophic resource pathways by:

1. increasing nutrient availability
2. providing additional substratum (surface area) for sessile organisms, algae and plants

ARs are beneficial for their positive impact on nutrient availability as well as for providing shelter. In fact, in addition to the increase in surface area previously indicated, **ARs should present vertical planes as well as holes and cavities.** This will also serve to improve nutrient circulation.

The number of studies directly addressing the relationship between the design of ARs and their potential impacts on the autotrophic communities is limited. In fact, most of existing studies focused on **autotrophs** examine the community composition, with much less attention paid to changes in NPP or in other processes of the ecosystems.

Autotrophs (Autotrophic organisms) capture that energy themselves from their environment and then build their own organic matter (sugars) from inorganic matter (carbon dioxide).

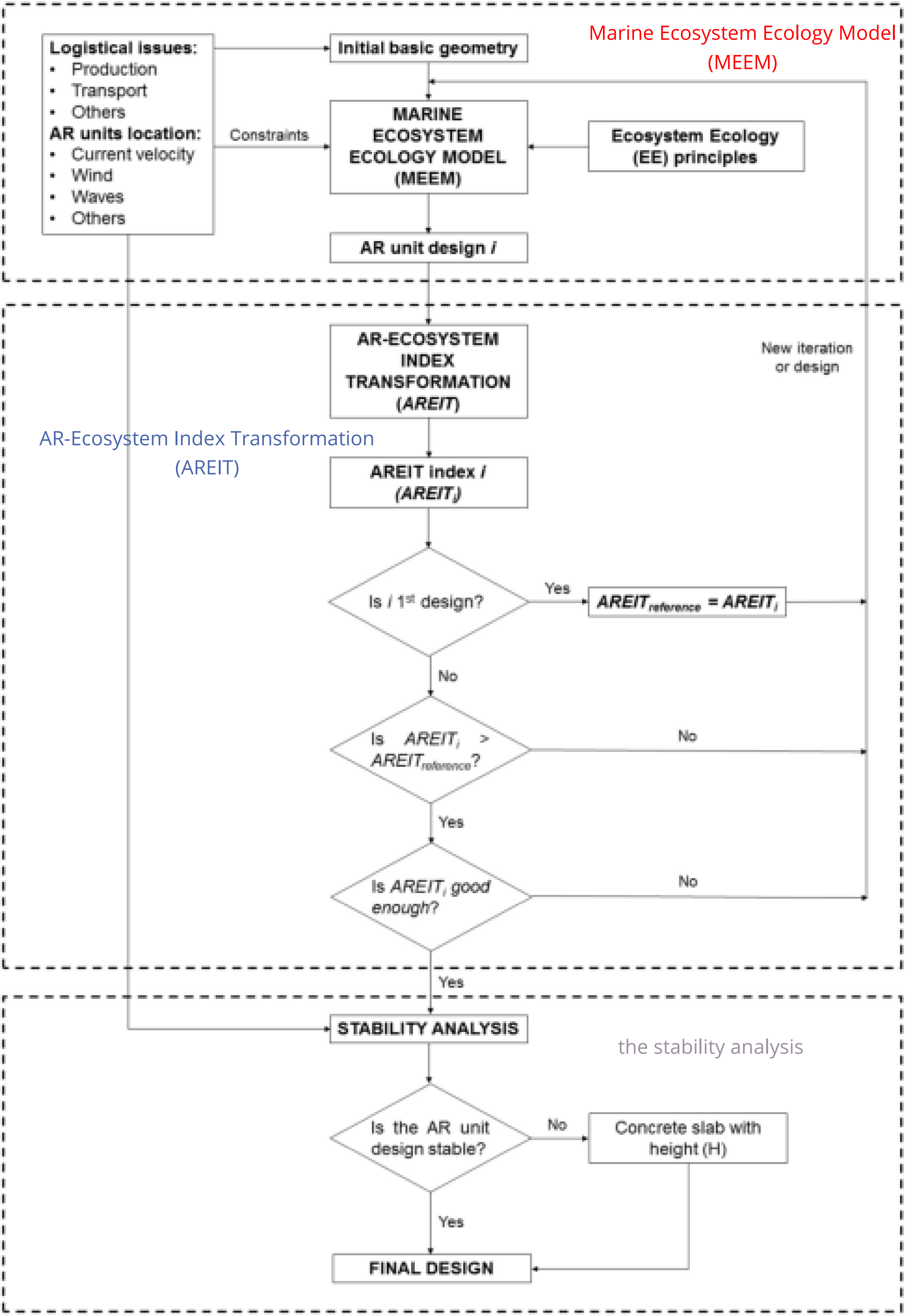
There is an analysis of the ecological effects of artificial substrata on marine environments and their biota. It highlighted the necessity of studying other factors (biological interactions and hydrodynamics or water currents, among others) when designing an artificial reef with the particularities of the ecosystem to be enhanced. There has been an EE perspective adopted and studied how the ecological mechanisms of Artificial Reefs can serve to maintain secondary production through NPP, decomposition and trophic interactions. Also with the objective of analysing the potential benefits of Artificial Reefs on fauna, biomass and diversity, it developed two artificial reef multimetric indices (ARMIs). Both indices consider **trophic structure, vulnerability, economic importance and structure of fish assemblages.**

- One of the indices (ARMIr) is for use on a global scale.
- The other one (ARMIe) measures the impact of the Artificial Reef in comparison with a control area in the same region.

the relationship between the design of an artificial reef and the secondary production of the ecosystem through the increase in NPP in all autotrophic pathways will be taken into account.

Conceptual Framework for the Design of AR Units

Flowchart of the conceptual framework proposed in this study. The dashed lines separate its three main parts: Marine Ecosystem Ecology Model (MEEM), AR-Ecosystem Index Transformation (AREIT), and the stability analysis.


Marine Ecosystem Ecology Model (MEEM)
Logistical issues:
• Production
• Transport
• Others
AR units location:
• Current velocity
• Wind
• Waves
• Others
Initial basic geometry
Constraints
MARINE ECOSYSTEM ECOLOGY MODEL (MEEM)
Ecosystem Ecology (EE) principles
AR unit design i
AR-ECOSYSTEM INDEX TRANSFORMATION (AREIT)
New iteration or design
AR-Ecosystem Index Transformation (AREIT)
AREIT index i ($AREIT_i$)
Is i 1st design?
Yes
$AREIT_{reference} = AREIT_i$
No
Is $AREIT_i$ > $AREIT_{reference}$?
No
Yes
Is $AREIT_i$ good enough?
No
Yes
STABILITY ANALYSIS
the stability analysis
Is the AR unit design stable?
No
Concrete slab with height (H)
Yes
FINAL DESIGN

Marine Ecosystem Ecology Model (MEEM)

See the Marine Ecosystem Ecology Model (MEEM). It starts from an initial basic geometry (a cube, a prism or a pyramid, among other possibilities) with specific dimensions and weight. The starting geometry takes into account all logistical issues (manufacturing and transport, among others) as well as all the necessary information (current velocity, seabed characteristics, and the effects of the wind, tide, waves and water discharges from rivers) at the location of the AR units.

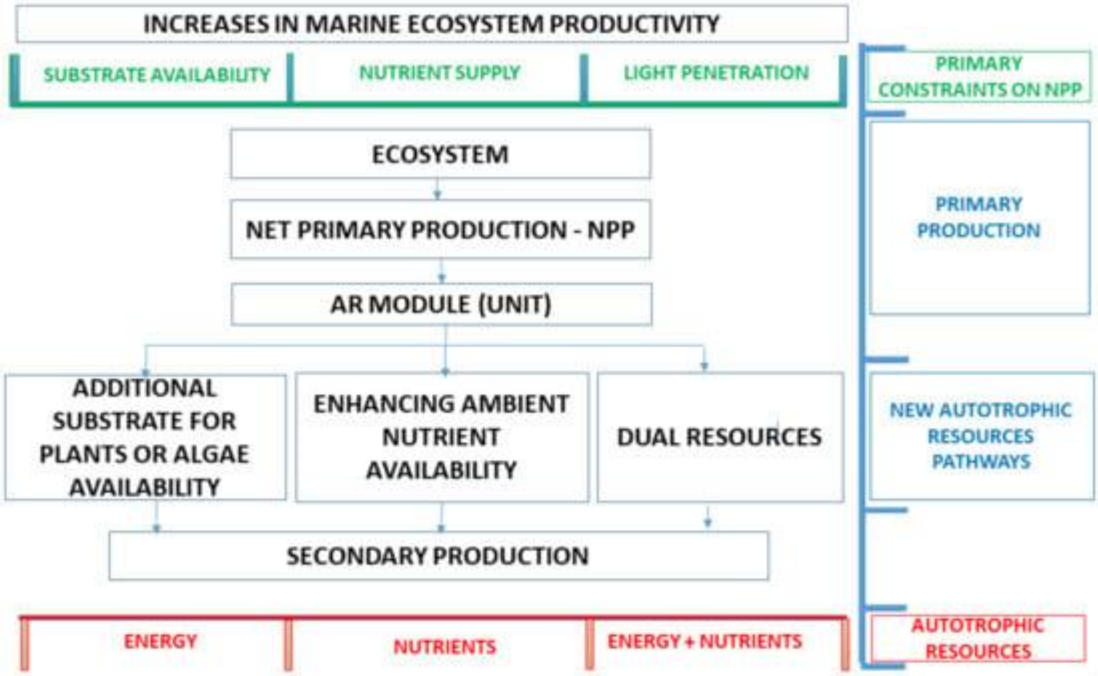
AR-Ecosystem Index Transformation (AREIT)

Together with the input information, MEEM uses ecosystem ecology (EE) principles to modify the initial geometry, mainly through the inclusion of holes and nest cavities. A nest cavity is a blind hole or a surface indentation and, unlike Biology 2022, 11, 680 4 of 20 other type of holes, it is not intended to connect different AR unit spaces but to provide more shelter. The number of holes and nest cavities as well as their dimensions are conditioned by the structural stresses that the AR unit will suffer during its life cycle, from the manufacture to the installation process. Nevertheless, as the result of following EE principles and taking into account the structural constraints, a wide range of different AR unit designs may arise. For such a purpose, the AREIT index is used as the second main part of the proposed framework.

this index preferably serves to measure the performance of those designs that contribute to the improvement of the ecosystem in terms of energy, nutrient availability and habitat. If a specific AR unit design does not contribute to one of the three previous dimensions, the complete AREIT index may not be used. The generation of new designs finishes when the result provided by this metric for one of the alternatives is good enough for the intended purpose. This usually means obtaining a sufficiently high overall index or obtaining a certain value for one or more of the three partial indices that make up AREIT (Section 2.3). Obviously, the iterative process of generating and assessing new AR unit designs can be transformed into a single or multi-objective mathematical constrained optimisation problem. Nevertheless, this is out of the scope of this study

The stability analysis

This analysis may lead to the inclusion of a concrete slab with a certain height (H in Figure 1). It is important to remark an alternative use of the proposed framework that affects the nomenclature of Figure 1, and that has already been indirectly introduced. There can be real situations in which the decision maker only needs to consider one or two of the three dimensions included in AREIT. This can be the case, for example, when an ecosystem presents problems in terms of energy or nutrient circulation, while additional shelter is not needed. In such cases, AREIT partial indices must be used as a benchmark for comparison among designs, instead of the overall index. It would also be possible to create a modified AREIT index by taking into account only the dimensions under study. In both circumstances, the selected index, as in the general case described here, will only serve to compare designs that contribute to the dimensions under consideration.



A submerged structure interacts with the aquatic environment, creating new attachment locations. Therefore, sessile organisms in a planktonic larval stage circulating through sea currents find new attachment surfaces. In this way, artificial reefs are first colonized by algae and sessile invertebrates, and their energy is consumed by vagile organisms such as crustaceans and herbivorous rockfish. These and other organisms will spawn at the artificial reefs and, predators and top predators will also find a place to shelter, feed and reproduce. As a result, artificial reefs increase both the energy and nutrient availability, boosting the food web of a specific ecosystem.

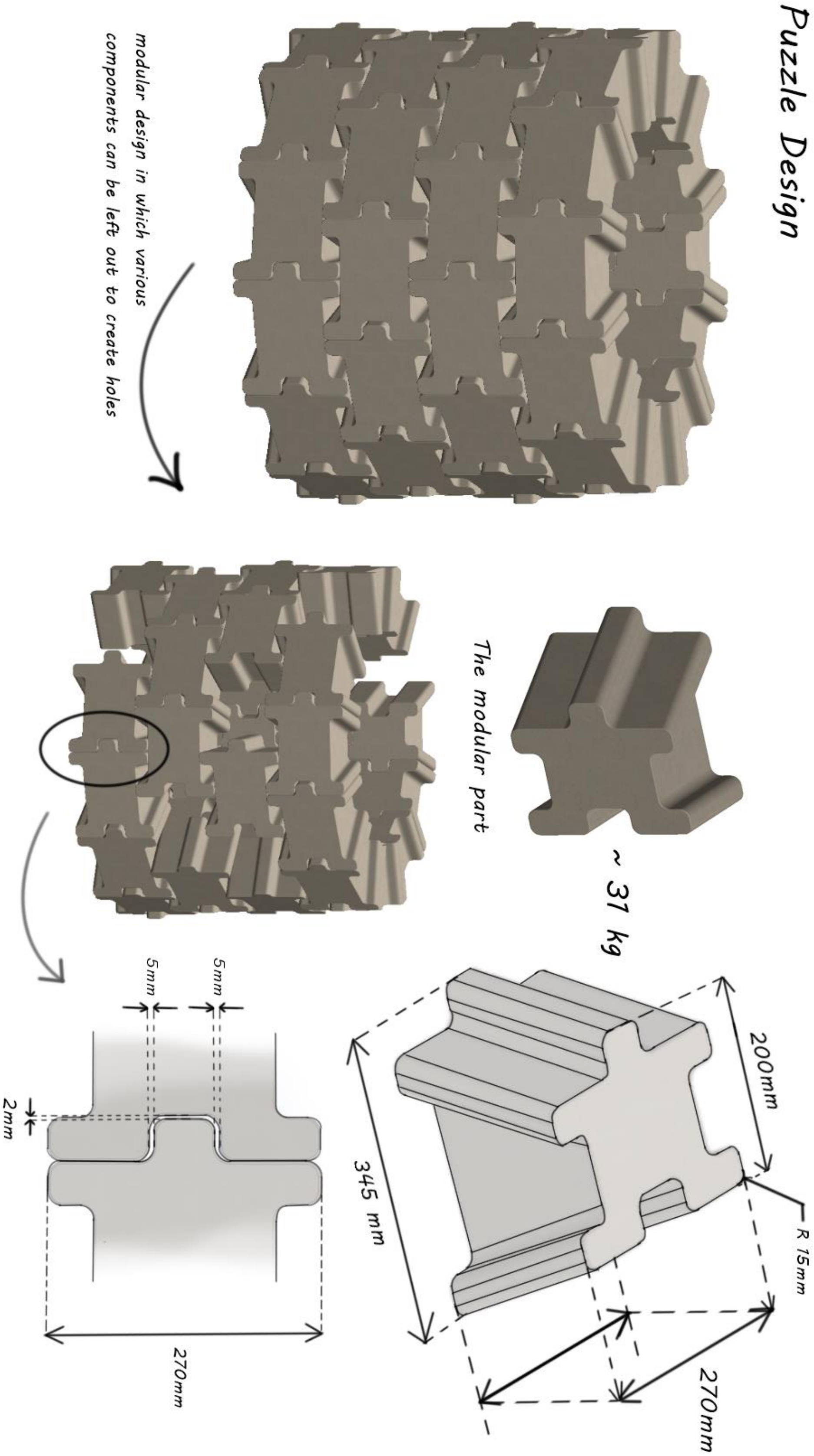
In describing the foundations of the MEEM model, it is necessary to consider a baseline design for the AR unit. In this case, taking into account the logistical processes of the management and enhancement of an estuary in Galicia by installing AR units [42], a cube with edges of 1.5 m appears to be a good option. The cube (upper prism) may need a concrete slab for stability purposes (third part of the conceptual framework, Section 2.4). This slab has no biological objectives and, consequently, it can be excluded from the AREIT index.

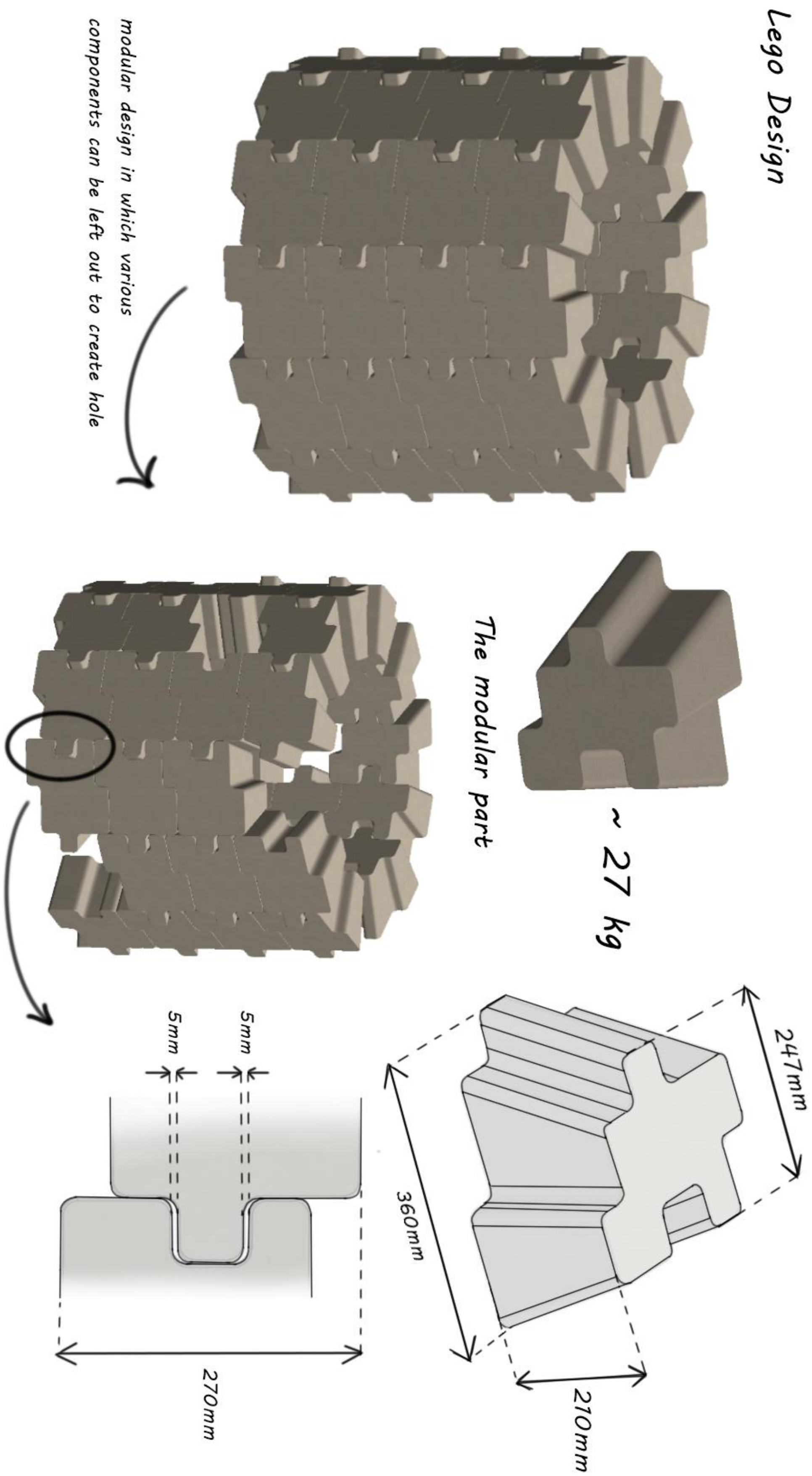
Determinant Factors		MEEM Model Foundations			
		Energy		Nutrients	Habitat for Settling Individuals
General Parameters	Specific Parameters	Substrate Availability	Light Supply	Nutrient Supply	
Material	AR material type	✓	-	-	-
	Material pH	✓	-	-	-
	Roughness	✓	-	-	-
Area	Area	✓	-	-	✓
Shape	Verticality	✓	X	✓	-
	Upper central hole	-	✓	-	-
	Lateral holes	X	-	✓	-
Nest cavities	Nest cavities (size)	-	-	-	✓
	Nest cavities (type)	-	-	-	✓
	Nest cavities number	-	-	-	✓

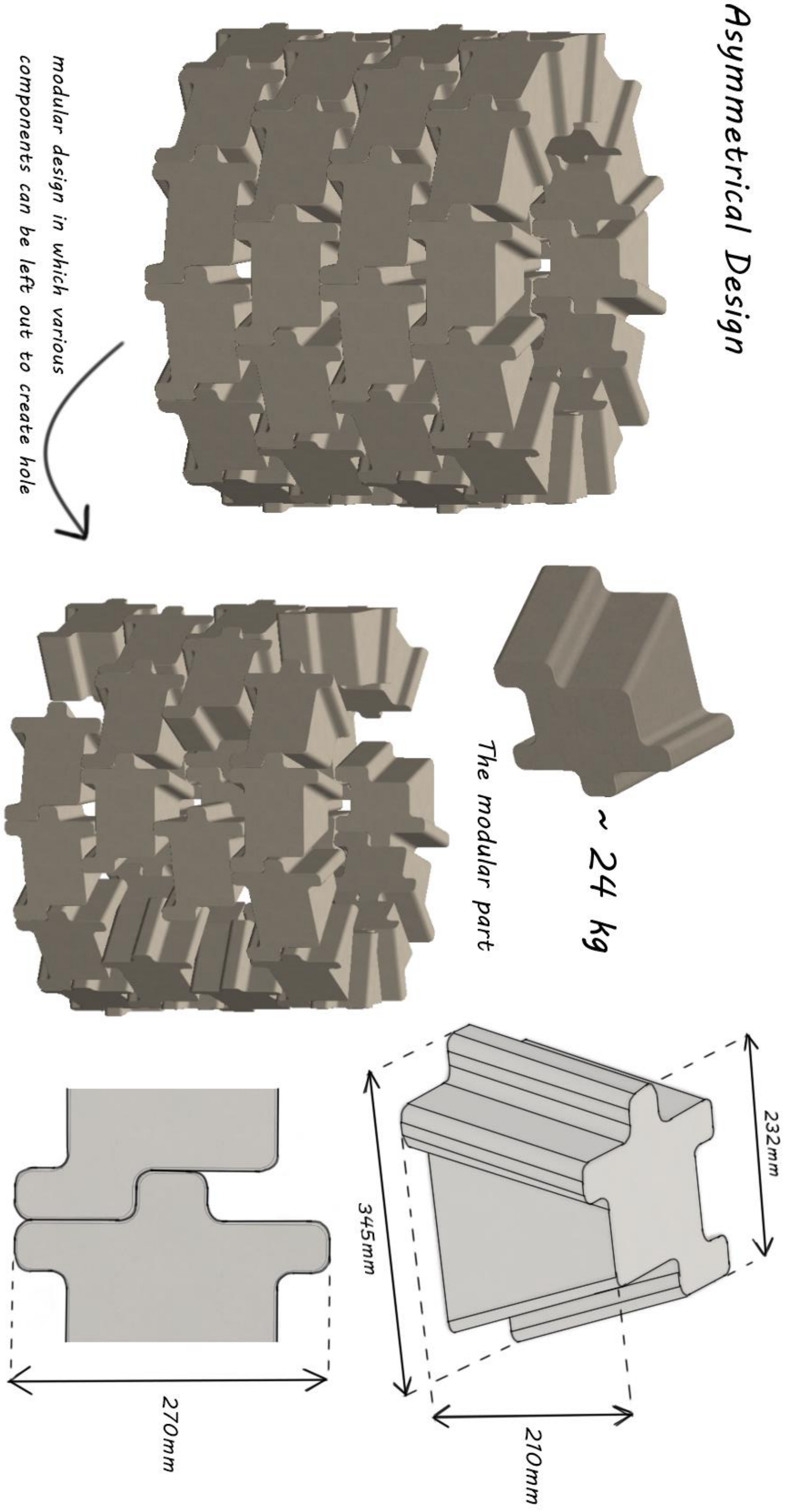
✓: Positive impact
X: Negative impact
-: No impact

Main parameters of an AR unit and their potential impacts in terms of energy, nutrients and new habitat.

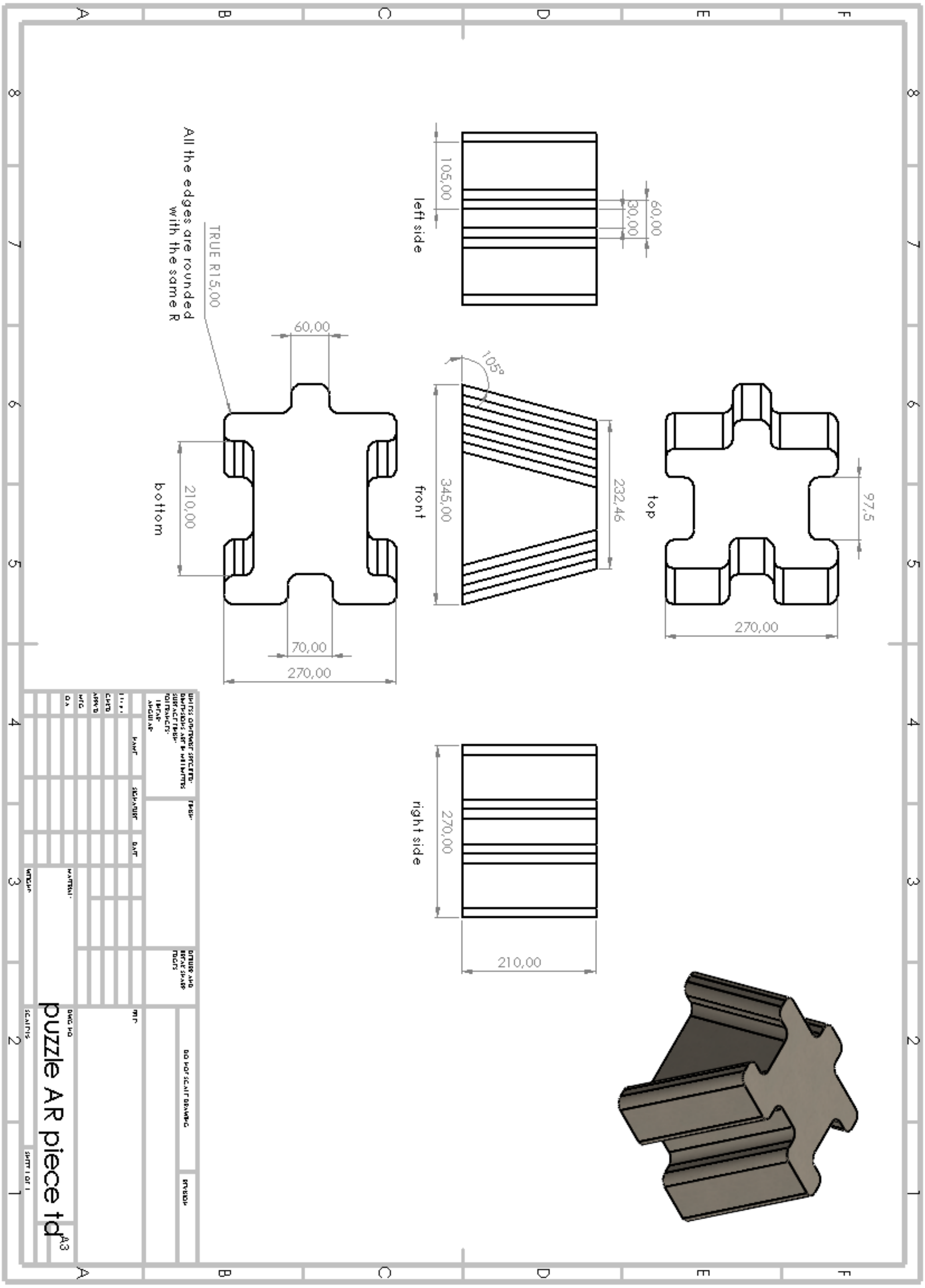
17.3 Presentation drawings

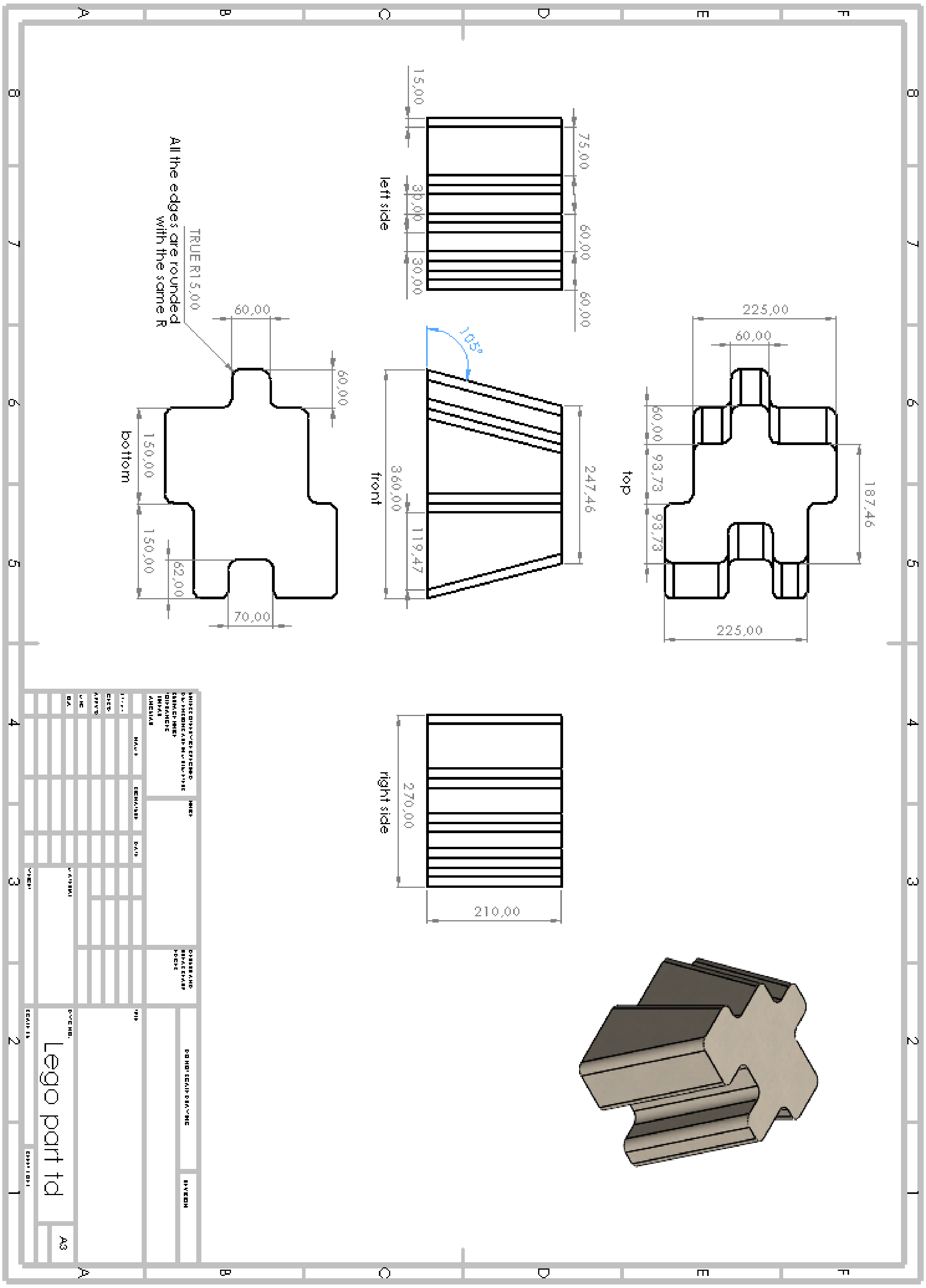


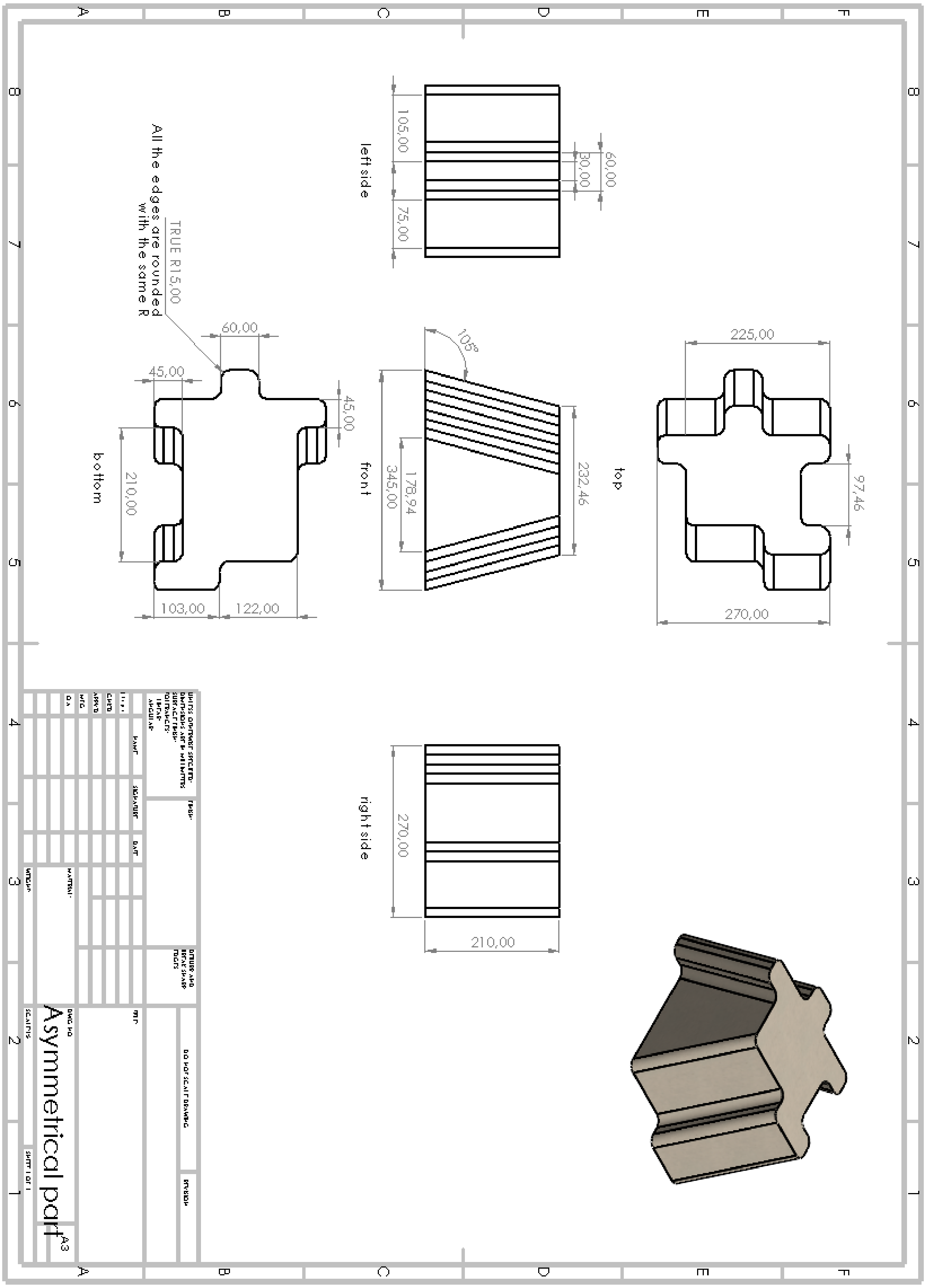

Lego Design
modular design in which various components can be left out to create hole
The modular part
~ 27 kg
5mm
5mm
270mm
360mm
247mm
210mm


Asymmetrical Design
modular design in which various components can be left out to create hole
The modular part
~ 24 kg
232mm
345mm
210mm
270mm

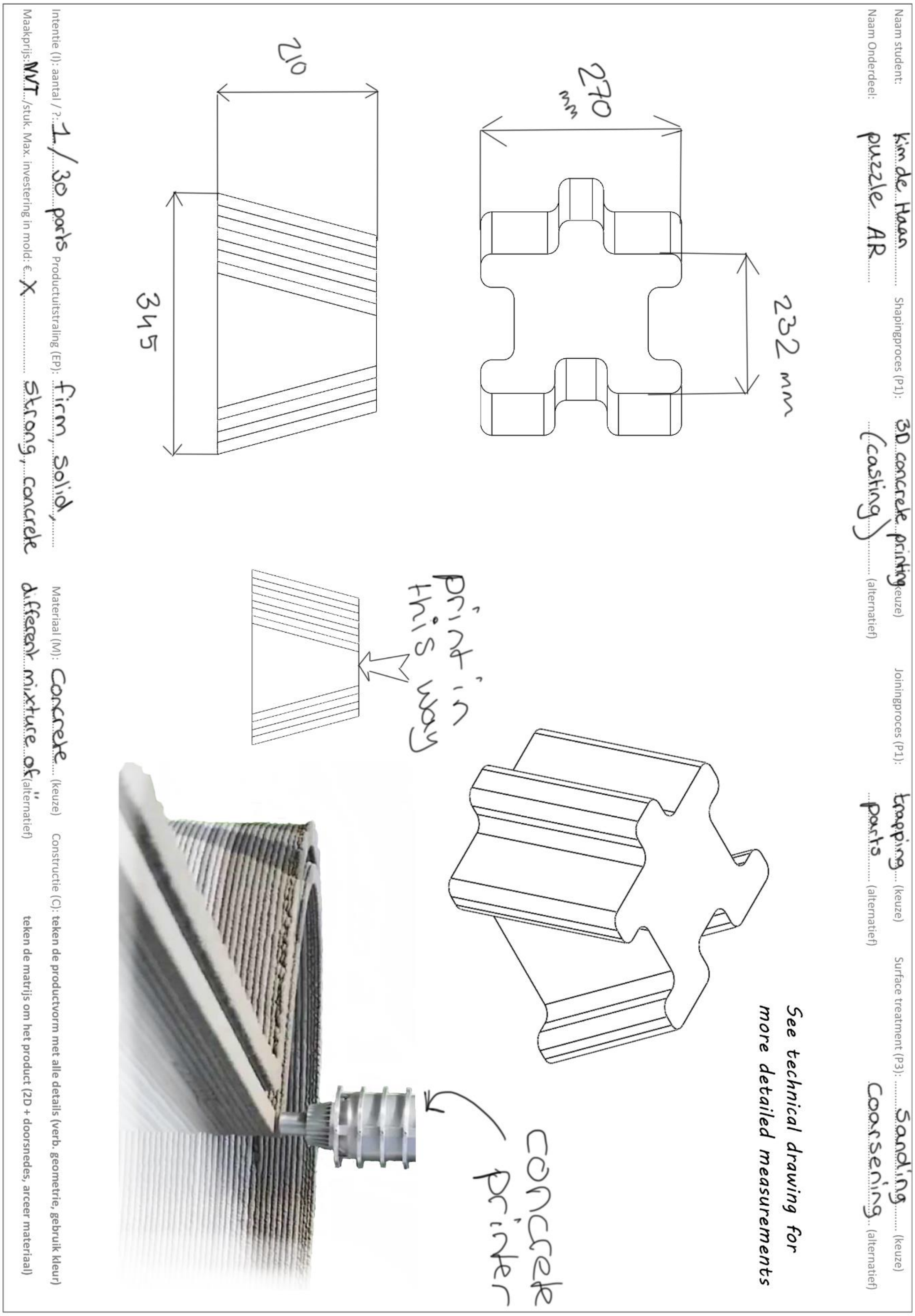
17.4 Technical drawings




left side
front
top
bottom
right side
All the edges are rounded with the same R
TRUE R15,00
105°
15,00
75,00
30,00
60,00
225,00
360,00
247,46
119,47
150,00
62,00
70,00
93,73
187,46
270,00
210,00
Lego part td
A3

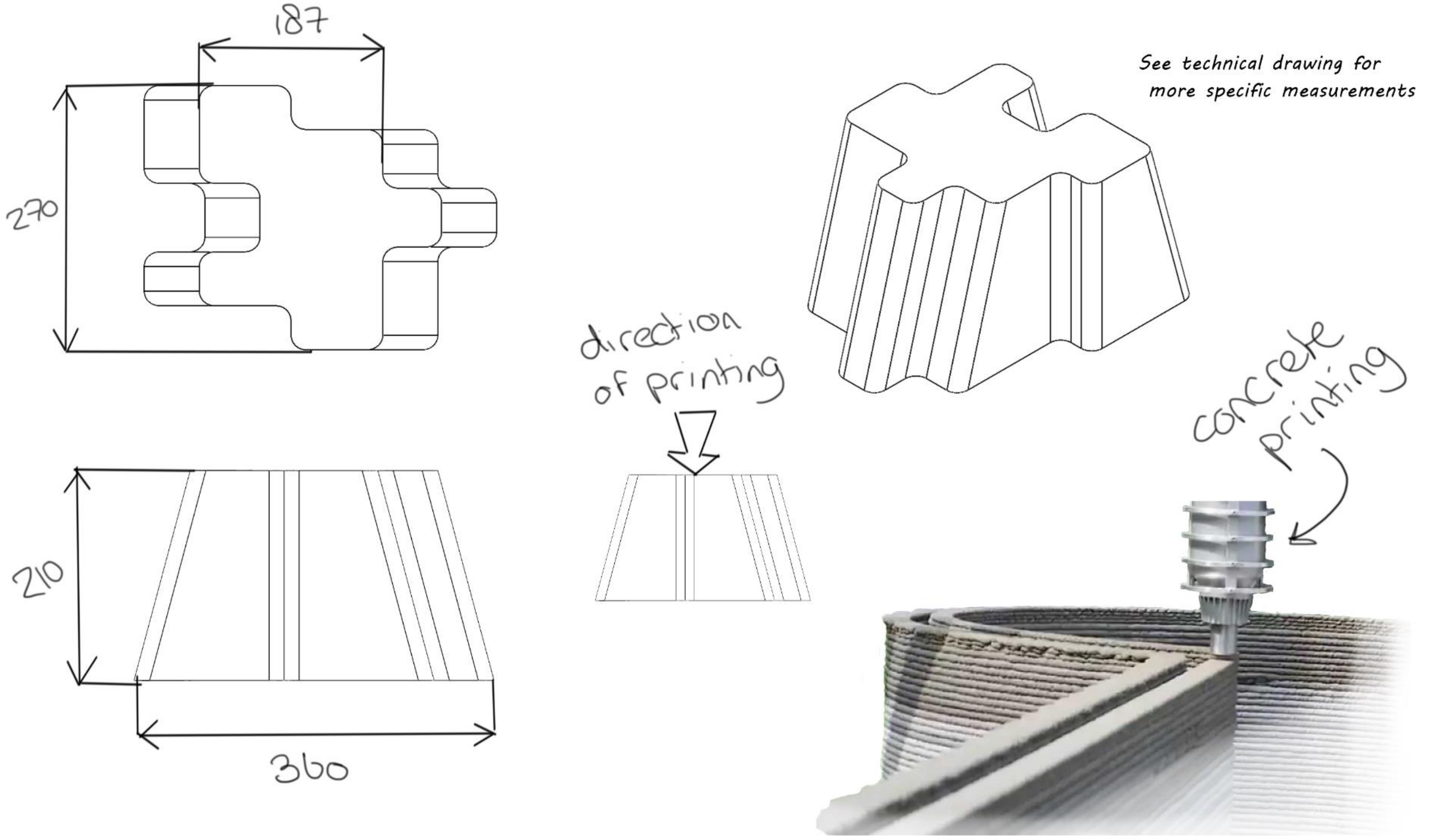

left side
105,00
75,00
30,00
60,00
TRUE R15,00
All the edges are rounded
with the same R
60,00
45,00
45,00
bottom
210,00
103,00
122,00
106°
front
345,00
178,94
232,46
top
225,00
97,46
270,00
right side
270,00
210,00
Asymmetrical part
A3

17.5 PCM drawings



Naam student: Kim de Haan Shapingproces (P1): 3D concrete printing (keuze) Joiningproces (P1): trapping (keuze) Surface treatment (P3): Sanding (keuze)

Naam Onderdeel: Lego AR (casting) (alternatief) parts (alternatief) Coarsening (alternatief)

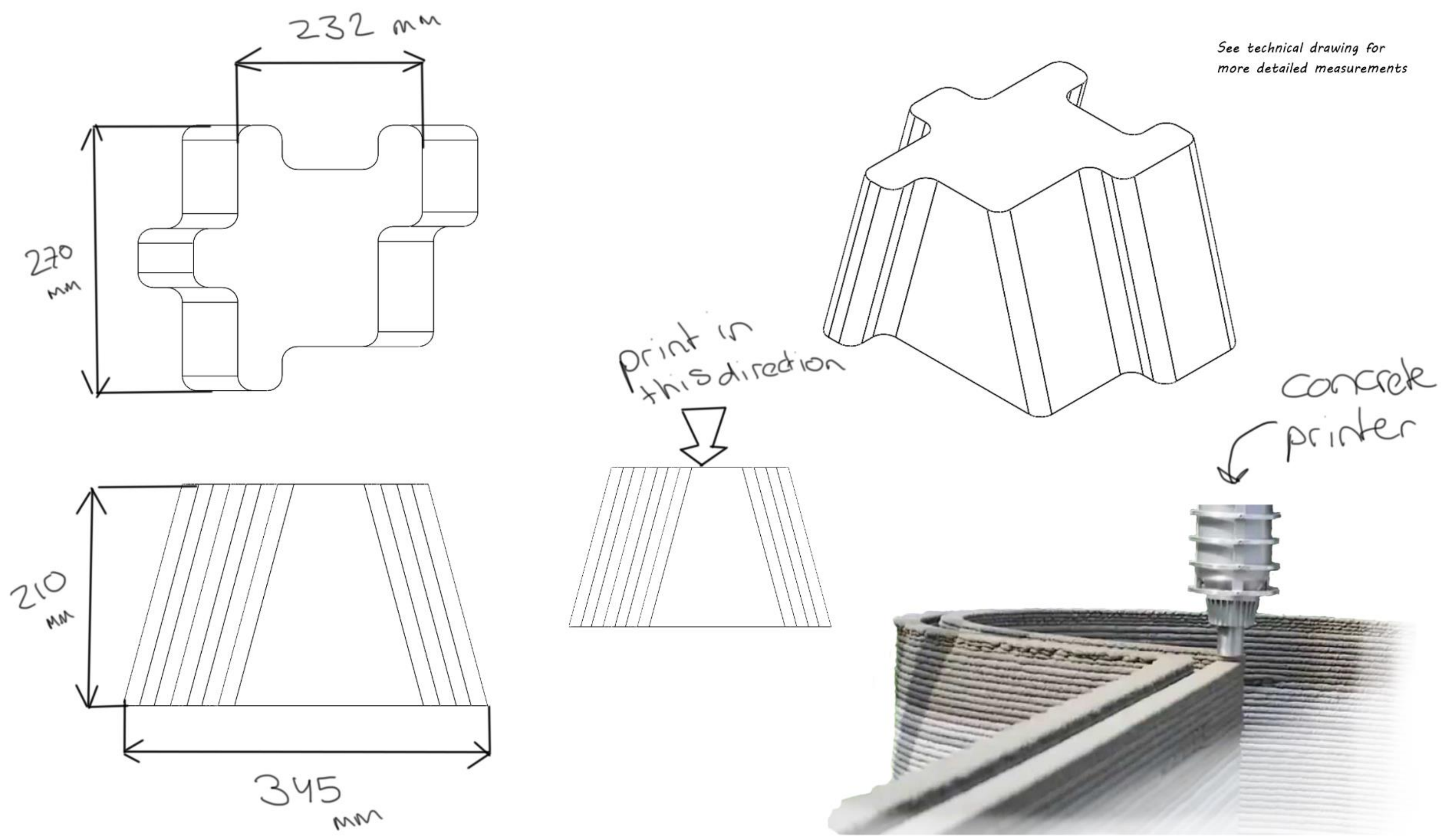


Intentie (I): aantal / ?: 1 / 30 parts Productuitstraling (EP): firm, solid, strong, concrete Materiaal (M): Concrete (keuze) different mixture of " (alternatief) Constructie (C): **teken de productvorm met alle details (verb. geometrie, gebruik kleur)**

Maakprijs: NVT /stuk. Max. investering in mold: € X **teken de matrijs om het product (2D + doorsnedes, arceer materiaal)**

Naam student: Kim de Haan | Shapingproces (P1): 3D concrete printing (keuze) | Joiningproces (P1): trapping (keuze) | Surface treatment (P3): Sanding (keuze)

Naam Onderdeel: Asymmetric AR | (casting) (alternatief) | parts (alternatief) | Coarsening (alternatief)



Intentie (I): aantal / ?: 1 / 30 parts Productuitstraling (EP): firm, solid, strong, concrete Materiaal (M): Concrete (keuze) different mixture of" (alternatief) Constructie (C): **teken de productvorm met alle details (verb. geometrie, gebruik kleur)**

Maakprijs: NVT /stuk. Max. investering in mold: € X **teken de matrijs om het product (2D + doorsnedes, arceer materiaal)**

17.6 ECO audit tool

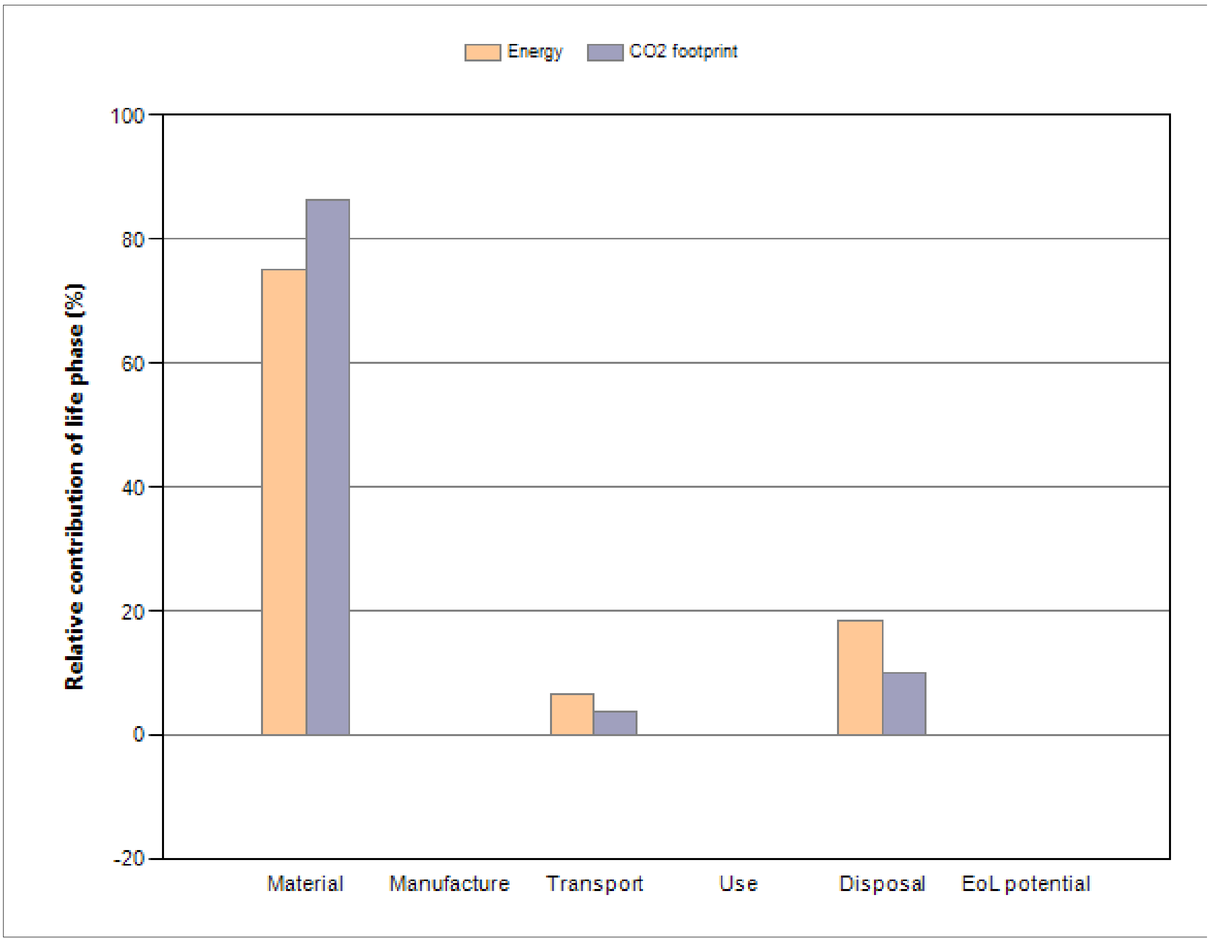
17.6.1 Puzzle reef 3 layers

GRANTA EduPack

Eco Audit Report

Product name	Puzzle reef 3 layers
Country of use	Spain
Product life (years)	20

Summary:



Energy details   CO2 footprint details

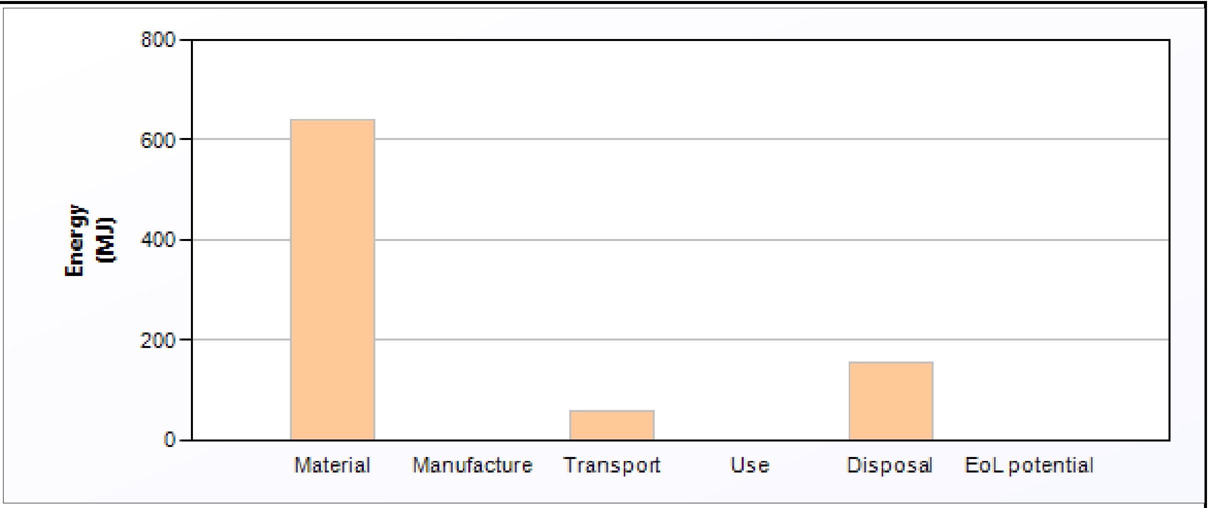
Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	638	75,0	95	86,4

Manufacture	0	0,0	0	0,0
Transport	56,3	6,6	4,06	3,7
Use	0	0,0	0	0,0
Disposal	156	18,3	10,9	9,9
Total (for first life)	**850**	**100**	**110**	**100**
End of life potential	0		0	

Eco Audit Report

Energy Analysis

[Summary]



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 20 year product life):	42,5

Detailed breakdown of individual life phases

Material:

[Summary]

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	Energy (MJ)	%
Puzzle part	Concrete	Virgin (0%)	26	30	7,8e+02	6,4e+02	100,0
Total				**30**	**7,8e+02**	**6,4e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

[Summary]

Component	Process	Amount processed	Energy (MJ)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	54	95,0
to the OBSEA area	Ocean freight	20	2,8	5,0
Total		**93**	**56**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Puzzle part	7,8e+02	56	100,0
Total	**7,8e+02**	**56**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	Energy (MJ)	%

Puzzle part	Landfill	1,6e+02	100,0
Total		**1,6e+02**	**100**

EoL potential:

Component	End of life option	Energy (MJ)	%
Puzzle part	Landfill	0	
Total		**0**	**100**

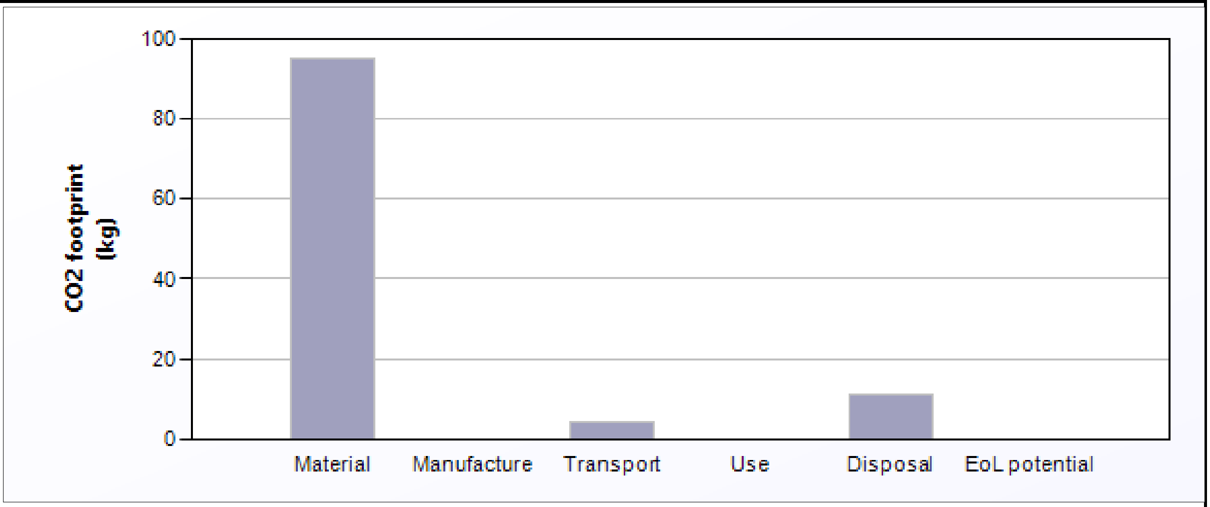
Notes:

Summary

Eco Audit Report

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 20 year product life):	5,5

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Puzzle part	Concrete	Virgin (0%)	26	30	7,8e+02	95	100,0
Total				**30**	**7,8e+02**	**95**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	CO2 footprint (kg)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	3,9	95,0
to the OBSEA area	Ocean freight	20	0,2	5,0
Total		**93**	**4,1**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Puzzle part	7,8e+02	4,1	100,0
Total	**7,8e+02**	**4,1**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	CO2 footprint (kg)	%
Puzzle part	Landfill	11	100,0
Total		**11**	**100**

EoL potential:

Component	End of life option	CO2 footprint (kg)	%
Puzzle part	Landfill	0	
Total		**0**	**100**

Notes:

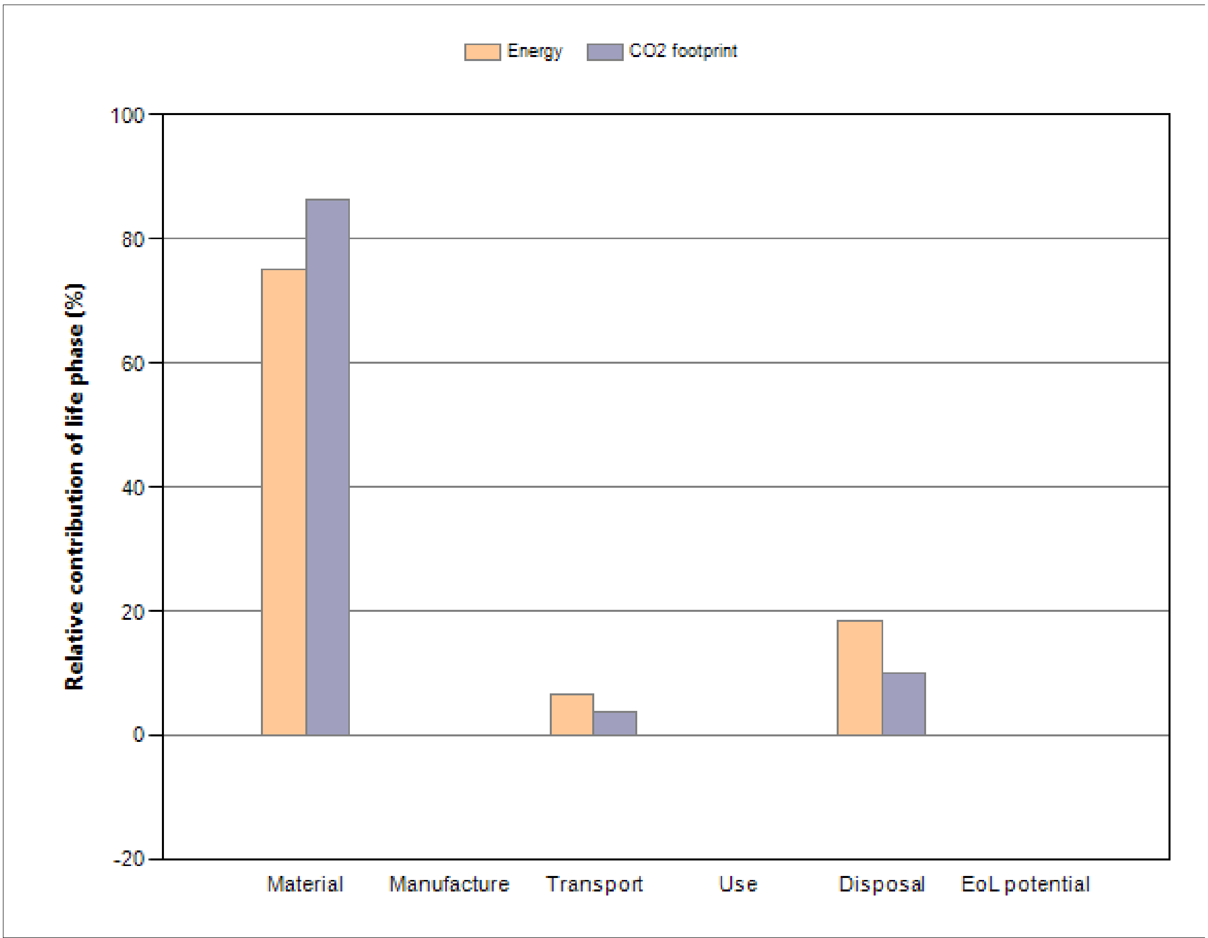
Summary

17.6.2 Puzzle reef 4 layers

Eco Audit Report

Product name	Artifical reefs
Country of use	Spain
Product life (years)	20

Summary:



Energy details   CO2 footprint details

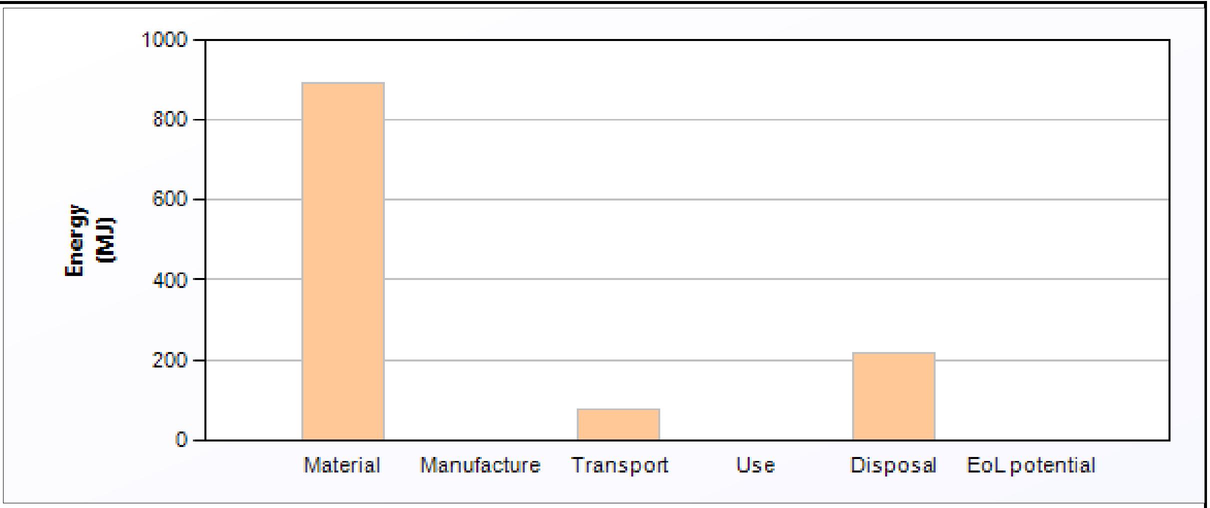
Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	893	75,0	133	86,4
Manufacture	0	0,0	0	0,0

Transport	78,9	6,6	5,68	3,7
Use	0	0,0	0	0,0
Disposal	218	18,3	15,3	9,9
Total (for first life)	**1,19e+03**	**100**	**154**	**100**
End of life potential	0		0	

Eco Audit Report

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 20 year product life):	59,5

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	Energy (MJ)	%
Puzzle reef - 4layers	Concrete	Virgin (0%)	1,1e+03	1	1,1e+03	8,9e+02	100,0
Total				**1**	**1,1e+03**	**8,9e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	Energy (MJ)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	75	95,0
to the OBSEA area	Ocean freight	20	3,9	5,0
Total		**93**	**79**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Puzzle reef - 4layers	1,1e+03	79	100,0
Total	**1,1e+03**	**79**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	Energy (MJ)	%

Puzzle reef - 4layers	Landfill	2,2e+02	100,0
Total		**2,2e+02**	**100**

EoL potential:

Component	End of life option	Energy (MJ)	%
Puzzle reef - 4layers	Landfill	0	
Total		**0**	**100**

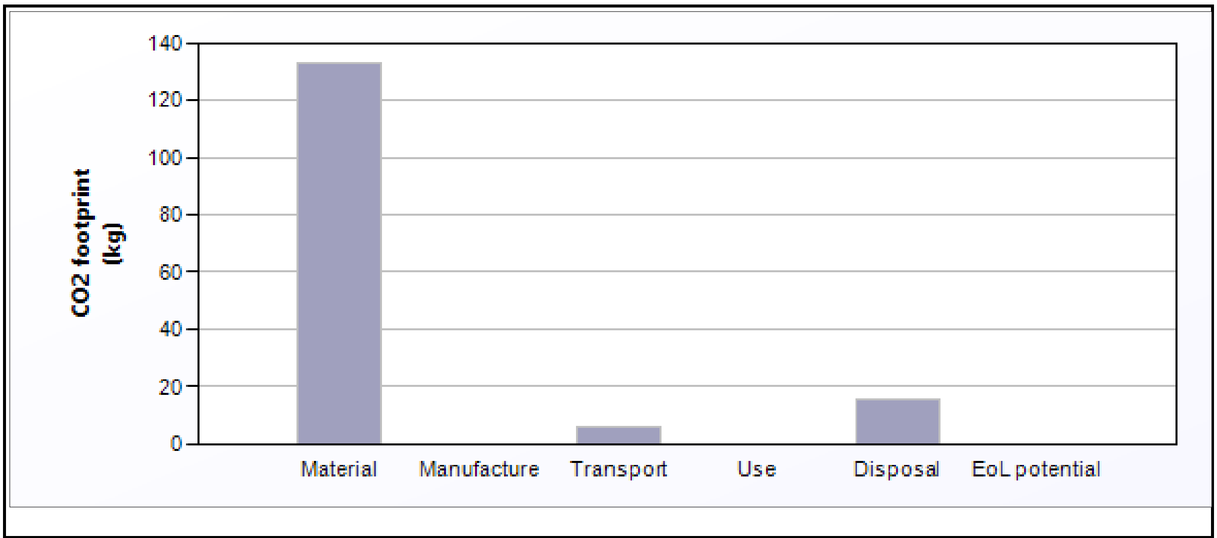
Notes:

Summary

Eco Audit Report

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 20 year product life):	7,7

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Puzzle reef - 4layers	Concrete	Virgin (0%)	1,1e+03	1	1,1e+03	1,3e+02	100,0
Total				**1**	**1,1e+03**	**1,3e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	CO2 footprint (kg)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	5,4	95,0
to the OBSEA area	Ocean freight	20	0,28	5,0
Total		**93**	**5,7**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Puzzle reef - 4layers	1,1e+03	5,7	100,0
Total	**1,1e+03**	**5,7**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	CO2 footprint (kg)	%
Puzzle reef - 4layers	Landfill	15	100,0
Total		**15**	**100**

EoL potential:

Component	End of life option	CO2 footprint (kg)	%
Puzzle reef - 4layers	Landfill	0	
Total		**0**	**100**

Notes:

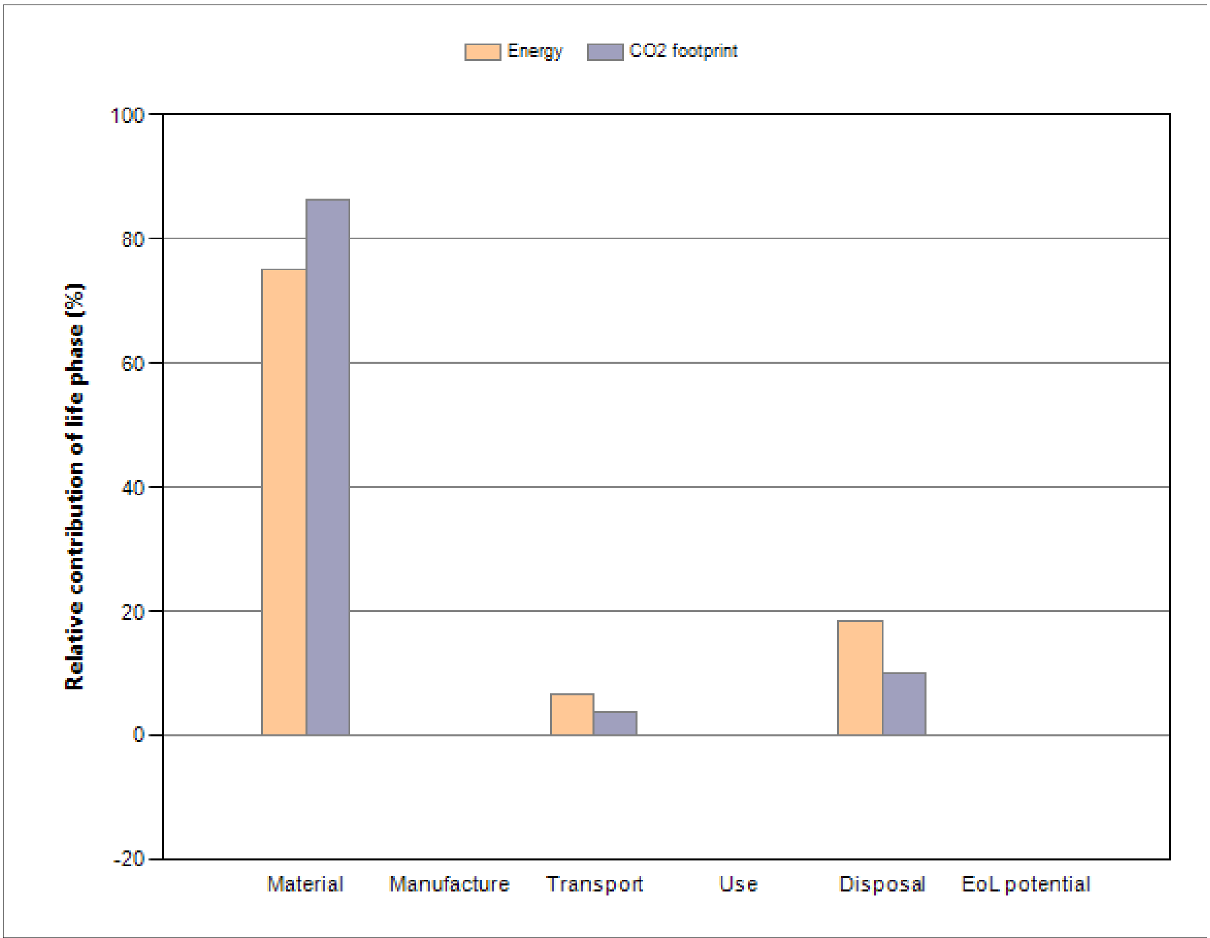
Summary

17.6.3 Lego reef 3 layers

Eco Audit Report

Product name	Lego reef 3 layers
Country of use	Spain
Product life (years)	20

Summary:



Energy details CO2 footprint details

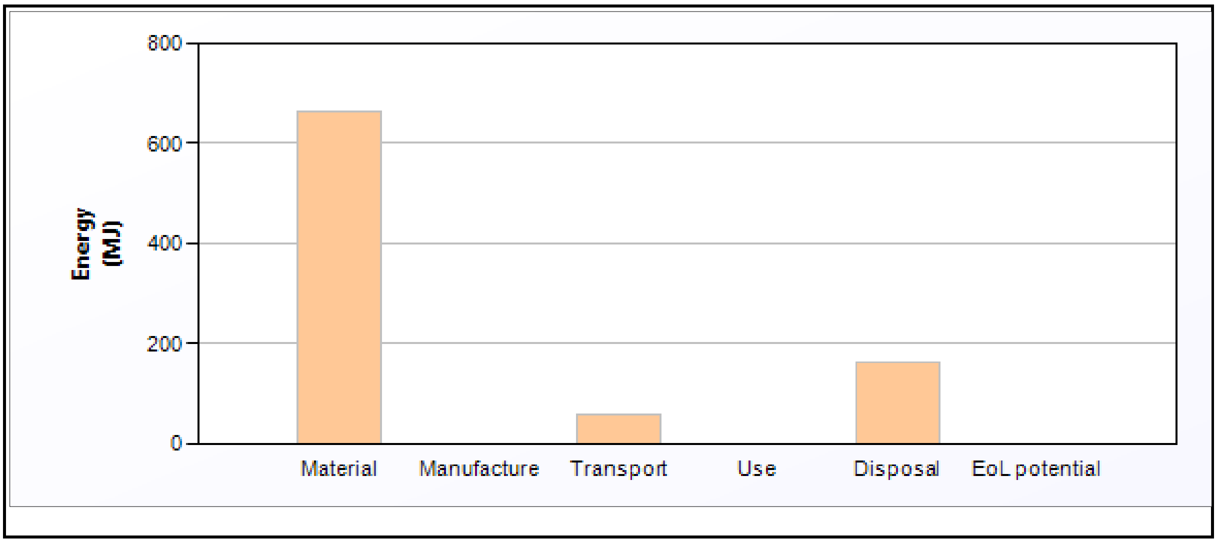
Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	663	75,0	98,7	86,4
Manufacture	0	0,0	0	0,0

Transport	58,5	6,6	4,21	3,7
Use	0	0,0	0	0,0
Disposal	162	18,3	11,3	9,9
Total (for first life)	**883**	**100**	**114**	**100**
End of life potential	0		0	

Eco Audit Report

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 20 year product life):	44,2

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	Energy (MJ)	%
Lego part	Concrete	Virgin (0%)	27	30	8,1e+02	6,6e+02	100,0
Total				**30**	**8,1e+02**	**6,6e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	Energy (MJ)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	56	95,0
to the OBSEA area	Ocean freight	20	2,9	5,0
Total		**93**	**58**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Lego part	8,1e+02	58	100,0
Total	**8,1e+02**	**58**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	Energy (MJ)	%

Lego part	Landfill	1,6e+02	100,0
Total		**1,6e+02**	**100**

EoL potential:

Component	End of life option	Energy (MJ)	%
Lego part	Landfill	0	
Total		**0**	**100**

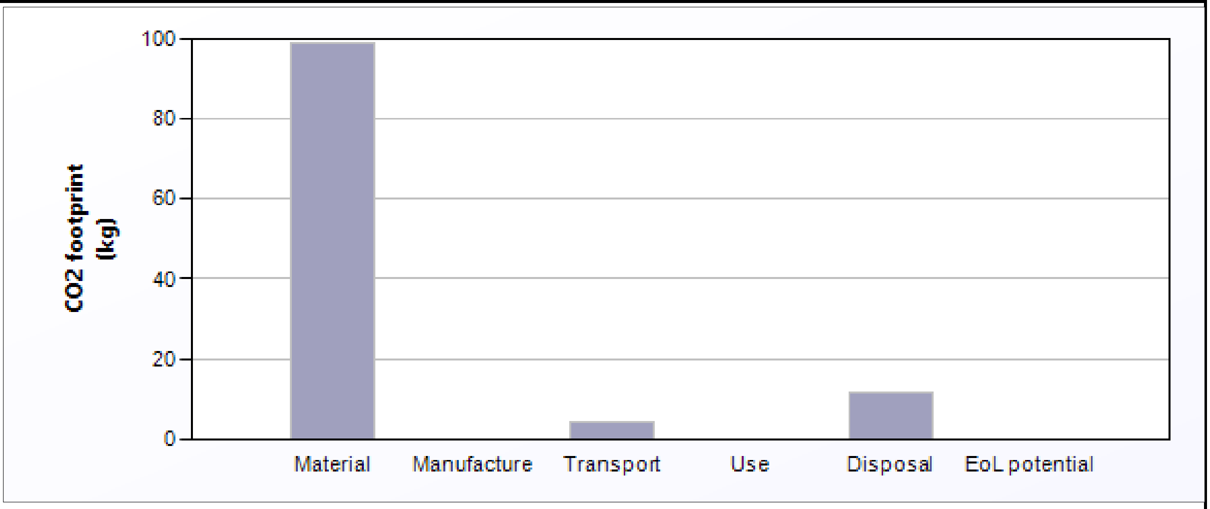
Notes:

Summary

Eco Audit Report

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 20 year product life):	5,71

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Lego part	Concrete	Virgin (0%)	27	30	8,1e+02	99	100,0
Total				**30**	**8,1e+02**	**99**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	CO2 footprint (kg)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	4	95,0
to the OBSEA area	Ocean freight	20	0,21	5,0
Total		**93**	**4,2**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Lego part	8,1e+02	4,2	100,0
Total	**8,1e+02**	**4,2**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	CO2 footprint (kg)	%
Lego part	Landfill	11	100,0
Total		**11**	**100**

EoL potential:

Component	End of life option	CO2 footprint (kg)	%
Lego part	Landfill	0	
Total		**0**	**100**

Notes:

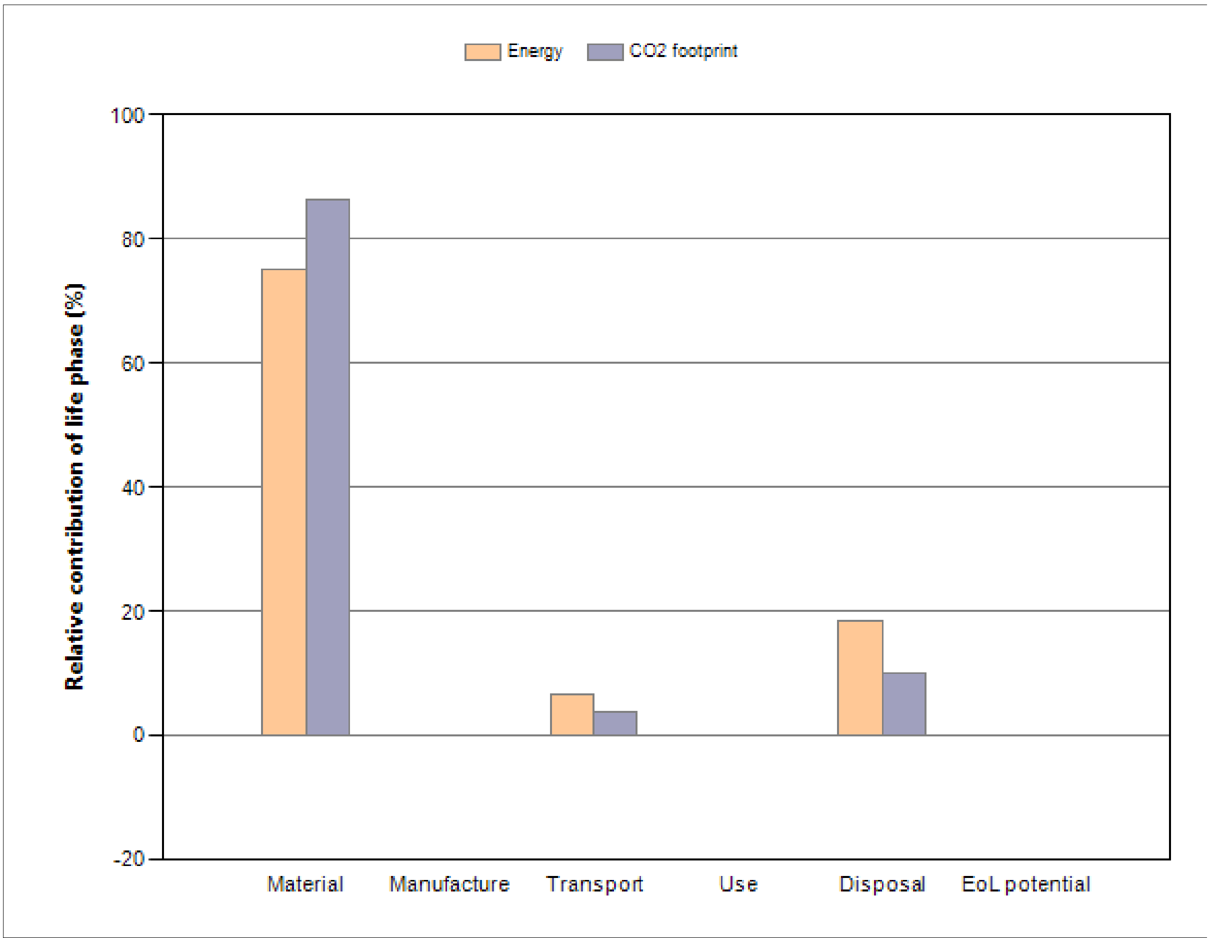
Summary

17.6.4 Lego reef 4 layers

Eco Audit Report

Product name	Lego reef 4 layers
Country of use	Spain
Product life (years)	20

Summary:



Energy details   CO2 footprint details

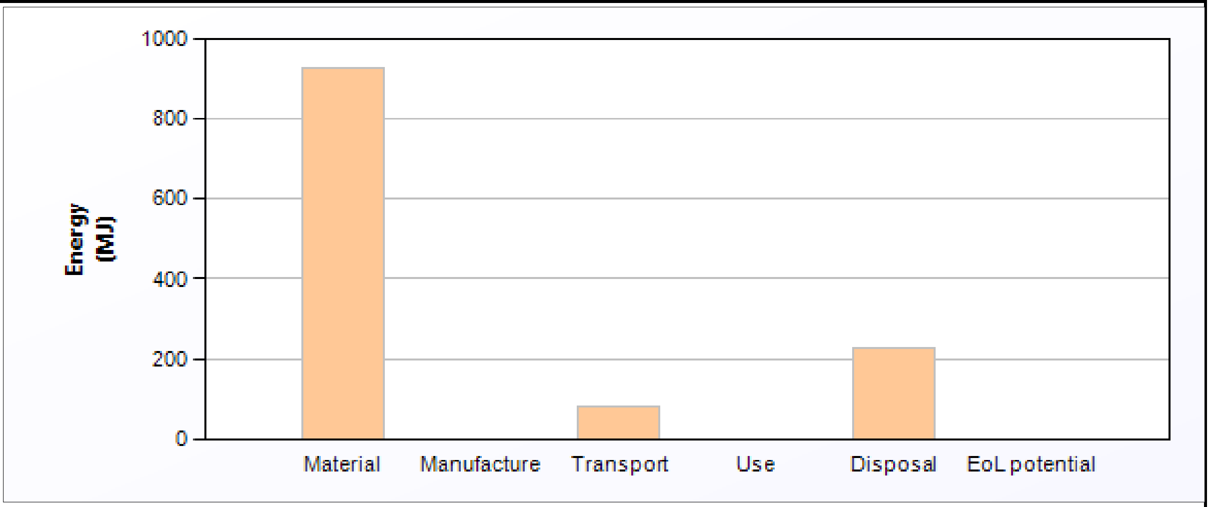
Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	928	75,0	138	86,4
Manufacture	0	0,0	0	0,0

Transport	81,9	6,6	5,9	3,7
Use	0	0,0	0	0,0
Disposal	227	18,3	15,9	9,9
Total (for first life)	**1,24e+03**	**100**	**160**	**100**
End of life potential	0		0	

Eco Audit Report

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 20 year product life):	61,8

Detailed breakdown of individual life phases

Material:

Summary

Component	**Material**	**Recycled content* (%)**	**Part mass (kg)**	**Qty.**	**Total mass (kg)**	**Energy (MJ)**	**%**
Lego part	Concrete	Virgin (0%)	27	42	1,1e+03	9,3e+02	100,0
Total				**42**	**1,1e+03**	**9,3e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	Energy (MJ)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	78	95,0
to the OBSEA area	Ocean freight	20	4,1	5,0
Total		**93**	**82**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Lego part	1,1e+03	82	100,0
Total	**1,1e+03**	**82**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	Energy (MJ)	%

Lego part	Landfill	2,3e+02	100,0
Total		**2,3e+02**	**100**

EoL potential:

Component	End of life option	Energy (MJ)	%
Lego part	Landfill	0	
Total		**0**	**100**

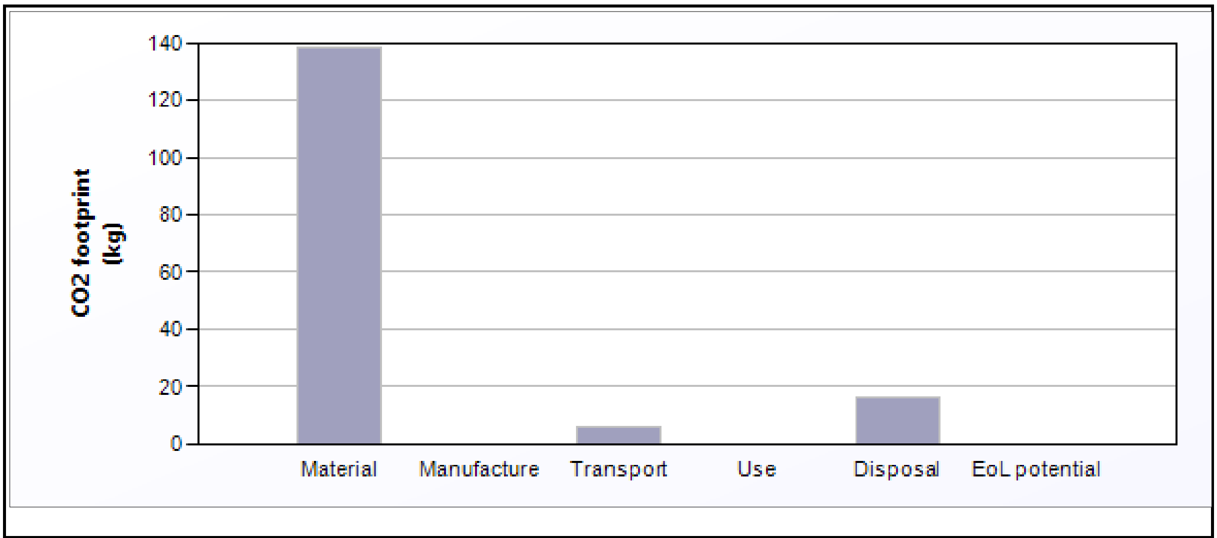
Notes:

Summary

Eco Audit Report

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 20 year product life):	8

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Lego part	Concrete	Virgin (0%)	27	42	1,1e+03	1,4e+02	100,0
Total				**42**	**1,1e+03**	**1,4e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	CO2 footprint (kg)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	5,6	95,0
to the OBSEA area	Ocean freight	20	0,29	5,0
Total		**93**	**5,9**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Lego part	1,1e+03	5,9	100,0
Total	**1,1e+03**	**5,9**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	CO2 footprint (kg)	%
Lego part	Landfill	16	100,0
Total		**16**	**100**

EoL potential:

Component	End of life option	CO2 footprint (kg)	%
Lego part	Landfill	0	
Total		**0**	**100**

Notes:

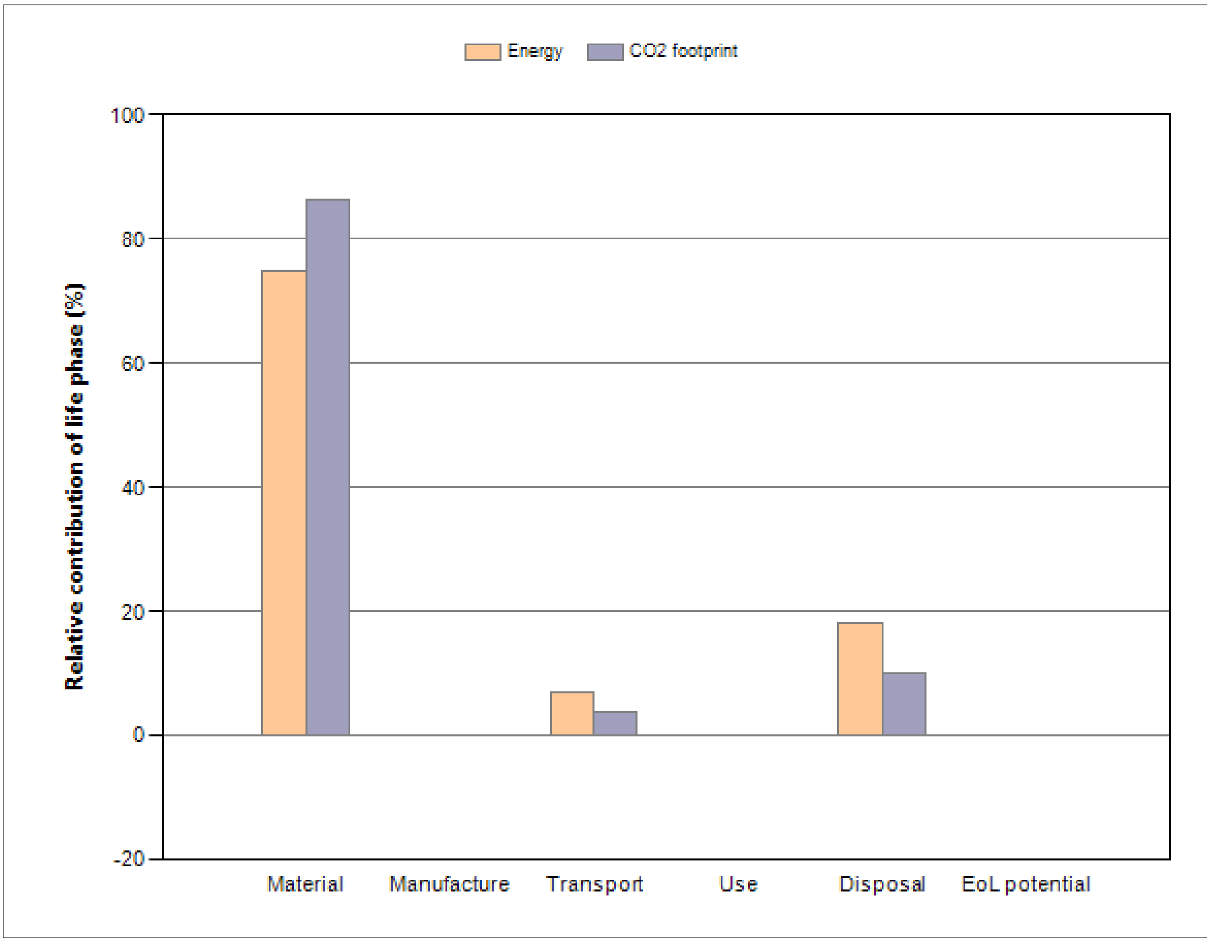
Summary

176.5 Asymmetrical reef 3 layers

Eco Audit Report

Product name	Asymmetrical reef 3 layers
Country of use	Spain
Product life (years)	20

Summary:



Energy details CO2 footprint details

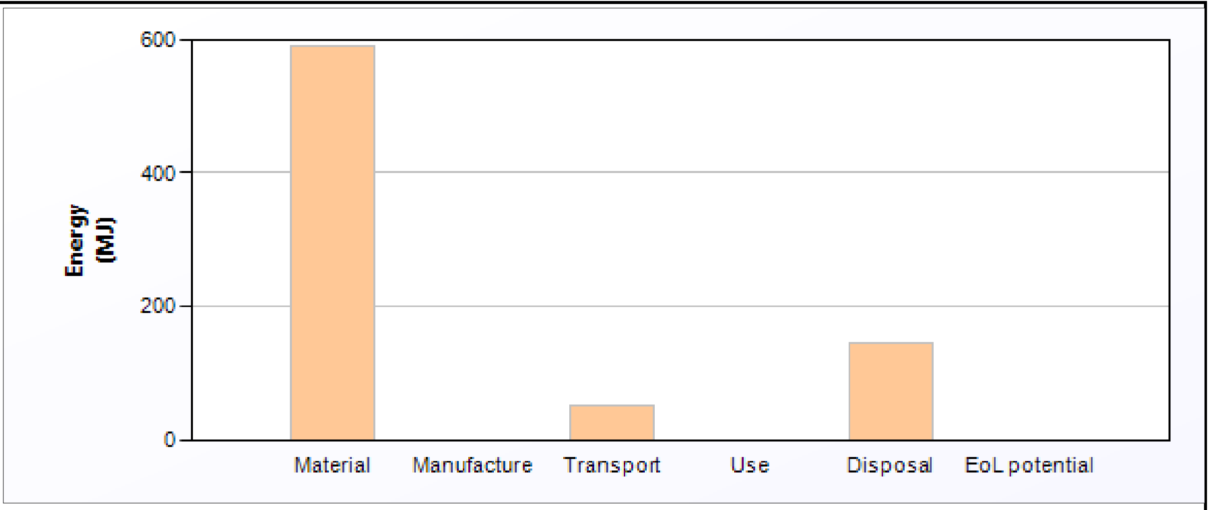
Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	589	74,9	87,7	86,3
Manufacture	0	0,0	0	0,0

Transport	53,3	6,8	3,84	3,8
Use	0	0,0	0	0,0
Disposal	144	18,3	10,1	9,9
Total (for first life)	**786**	**100**	**102**	**100**
End of life potential	0		0	

Eco Audit Report

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 20 year product life):	39,3

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	Energy (MJ)	%
Asymmetrical part	Concrete	Virgin (0%)	24	30	7,2e+02	5,9e+02	100,0
Total				**30**	**7,2e+02**	**5,9e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	Energy (MJ)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	49	92,7
to the OBSEA area	Coastal freight	20	3,9	7,3
Total		**93**	**53**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Asymmetrical part	7,2e+02	53	100,0
Total	**7,2e+02**	**53**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	Energy (MJ)	%

Asymmetrical part	Landfill	1,4e+02	100,0
Total		**1,4e+02**	**100**

EoL potential:

Component	**End of life option**	**Energy (MJ)**	**%**
Asymmetrical part	Landfill	0	
Total		**0**	**100**

Notes:

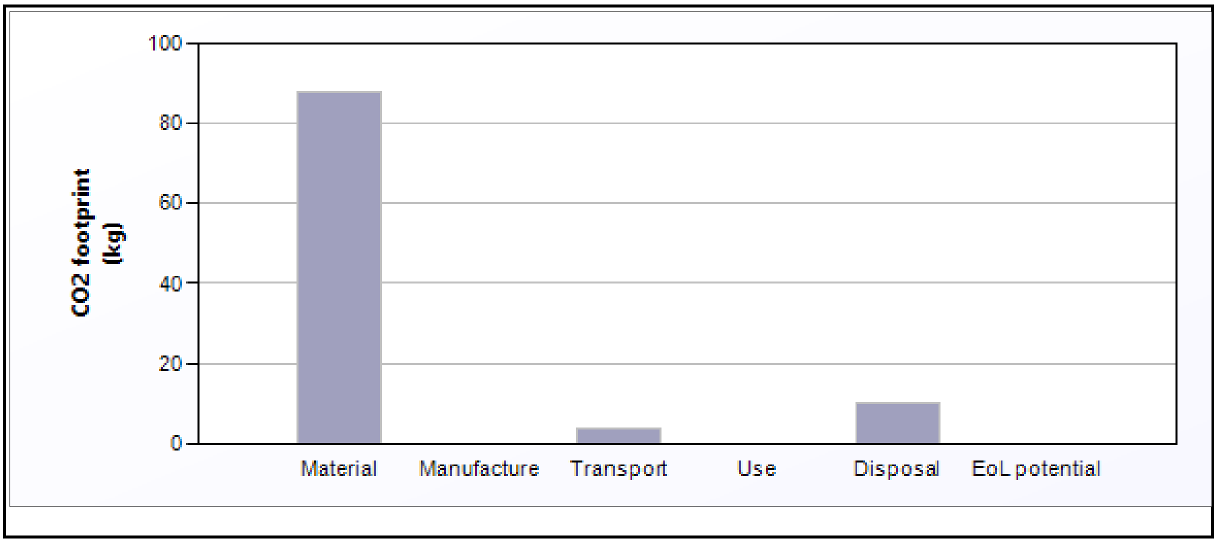
Summary

Eco Audit Report

GRANTA EduPack

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 20 year product life):	5,08

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Asymmetrical part	Concrete	Virgin (0%)	24	30	7,2e+02	88	100,0
Total				**30**	**7,2e+02**	**88**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	CO2 footprint (kg)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	3,6	92,7
to the OBSEA area	Coastal freight	20	0,28	7,3
Total		**93**	**3,8**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Asymmetrical part	7,2e+02	3,8	100,0
Total	**7,2e+02**	**3,8**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	CO2 footprint (kg)	%
Asymmetrical part	Landfill	10	100,0
Total		**10**	**100**

EoL potential:

Component	End of life option	CO2 footprint (kg)	%
Asymmetrical part	Landfill	0	
Total		**0**	**100**

Notes:

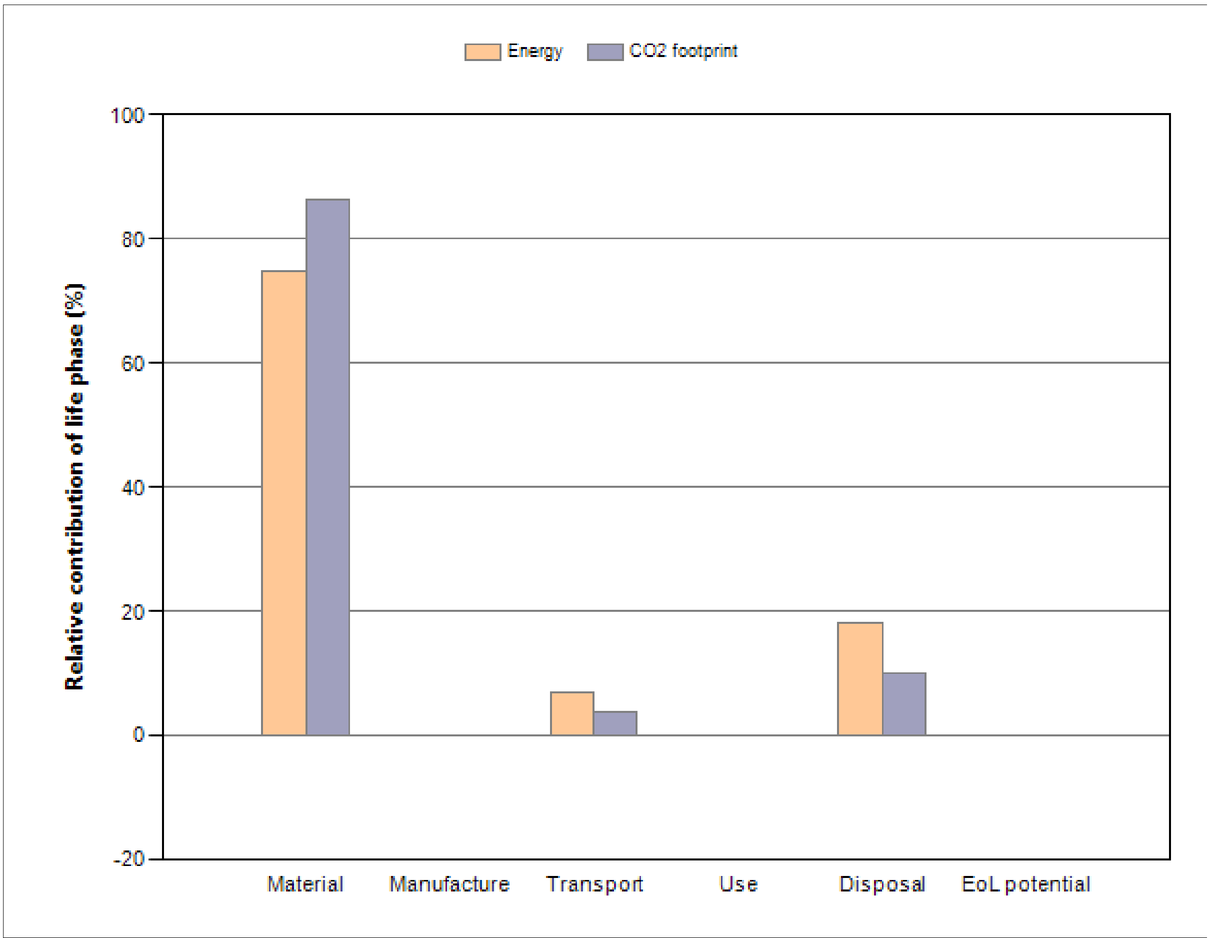
Summary

17.6.6 Asymmetrical reef 4 layers

Eco Audit Report

Product name	Asymmetrical reef 4 layers
Country of use	Spain
Product life (years)	20

Summary:



Energy details   CO2 footprint details

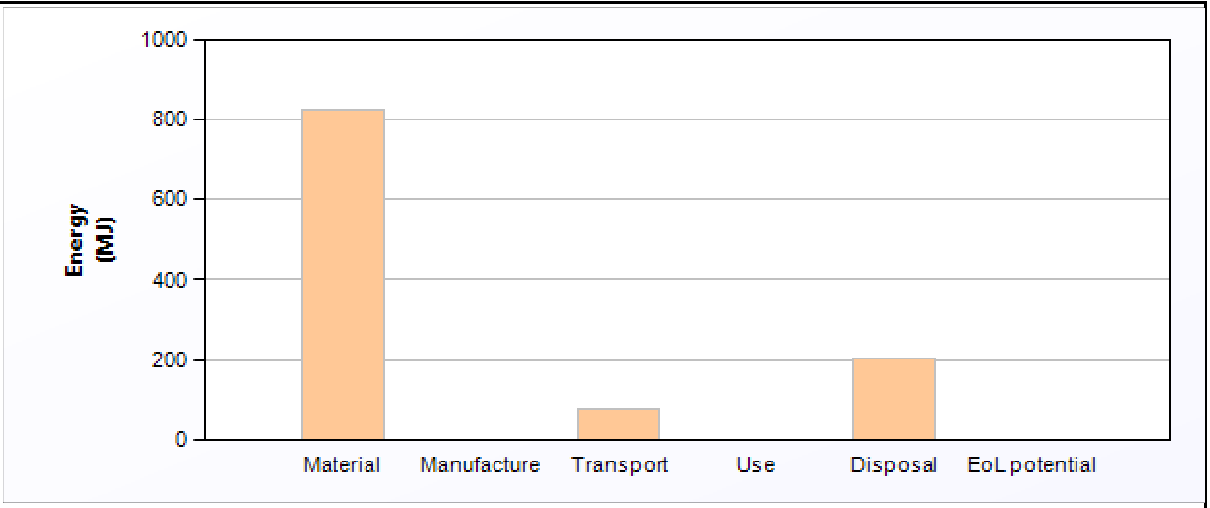
Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	825	74,9	123	86,3
Manufacture	0	0,0	0	0,0

Transport	74,6	6,8	5,37	3,8
Use	0	0,0	0	0,0
Disposal	202	18,3	14,1	9,9
Total (for first life)	**1,1e+03**	**100**	**142**	**100**
End of life potential	0		0	

Eco Audit Report

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 20 year product life):	55

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	Energy (MJ)	%
Asymmetrical part	Concrete	Virgin (0%)	24	42	1e+03	8,2e+02	100,0
Total				**42**	**1e+03**	**8,2e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	Energy (MJ)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	69	92,7
to the OBSEA area	Coastal freight	20	5,4	7,3
Total		**93**	**75**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Asymmetrical part	1e+03	75	100,0
Total	**1e+03**	**75**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	Energy (MJ)	%
Asymmetrical part	Landfill	2e+02	100,0
Total		**2e+02**	**100**

EoL potential:

Component	End of life option	Energy (MJ)	%
Asymmetrical part	Landfill	0	
Total		**0**	**100**

Notes:

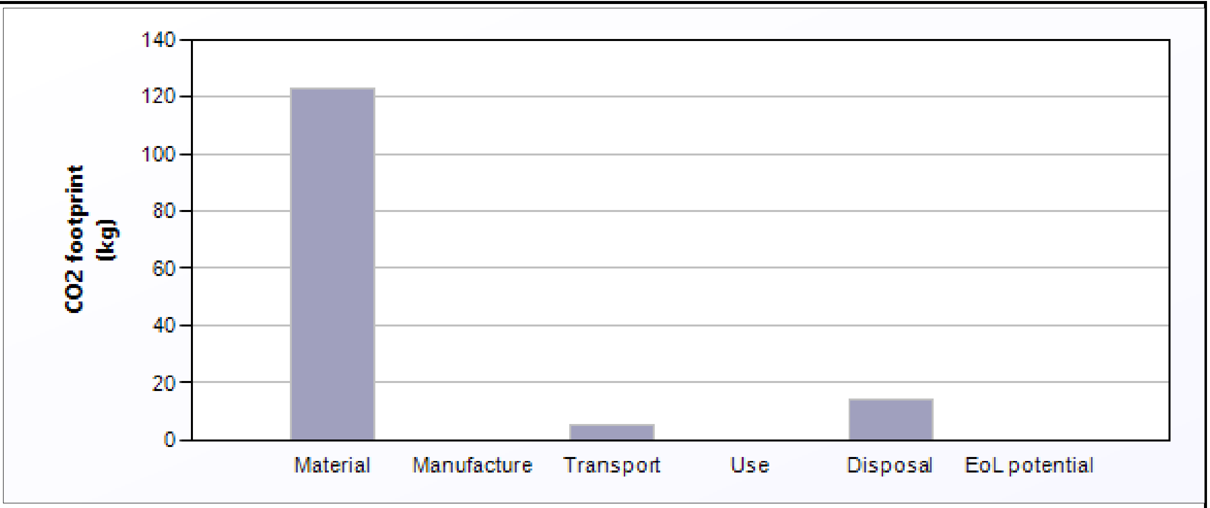
Summary

Eco Audit Report

GRANTA EduPack

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 20 year product life):	7,12

Detailed breakdown of individual life phases

Material:

Summary

Component	**Material**	**Recycled content* (%)**	**Part mass (kg)**	**Qty.**	**Total mass (kg)**	**CO2 footprint (kg)**	**%**
Asymmetrical part	Concrete	Virgin (0%)	24	42	1e+03	1,2e+02	100,0
Total				**42**	**1e+03**	**1,2e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

Manufacture:

Summary

Component	Process	Amount processed	CO2 footprint (kg)	%
Total				**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
to harbor Vilanova	32 tonne (4 axle) truck	73	5	92,7
to the OBSEA area	Coastal freight	20	0,39	7,3
Total		**93**	**5,4**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Asymmetrical part	1e+03	5,4	100,0
Total	**1e+03**	**5,4**	**100**

Use:

Summary

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	**0**	**100**

Disposal:

Summary

Component	End of life option	CO2 footprint (kg)	%
Asymmetrical part	Landfill	14	100,0
Total		**14**	**100**

EoL potential:

Component	End of life option	CO2 footprint (kg)	%
Asymmetrical part	Landfill	0	
Total		**0**	**100**

Notes:

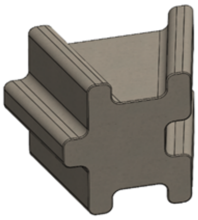
Summary

Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú
UNIVERSITAT POLITÈCNICA DE CATALUNYA

17.7 AREIT Calculation

PUZZLE : DESIGN 1

	Name	cm²
1	top	322,8344
2	sidepic	97,8336
3	toppic	94,5
4	side	228,2784
5	hside	217,408
6	sidehole	98,7
7	tophole	152,1856
8	sidesquare	94,5
9	topsquare	130,4448
10	front	412,5304
11	back	615,1
12	trapezium	137,1754
13	small trapezium	72,8622
14	surplus ext_h	9,1364
15	surplus ext_v	12,74
16	surplus int_h	9,928818
17	surplus int_v	15,451434



4 layers

Number of pieces	42
Number of surplus	36

Horizontal surface	6828,36065
Vertical Surface	44175,3684

	Sholes_v	Sholes_h	Total	Quantity
1	1565,3376	1313,1016	2878,4392	6
2	195,6672	145,7244	341,3916	46
Total	18392,7168	14581,932	32974,6488	52

Total horizontal surface	Sh= 21410,2926
Total vertical surface	Sv= 62568,0852

3 layers

Number of pieces	30
Number of surplus	24

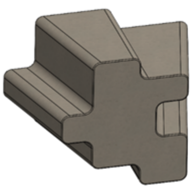
Horizontal surface	7613,32723
Vertical Surface	35614,5176

	Sholes_v	Sholes_h	Total	Quantity
1	1565,3376	1313,1016	2878,4392	6
2	195,6672	145,7244	341,3916	46
Total	18392,7168	14581,932	32974,6488	52

Total horizontal surface	Sh= 22195,2592
Total vertical surface	Sv= 54007,2344

LEGO : DESIGN 2

	Name	cm²
1	top	255,9172
2	upside	119,5744
3	sidehole	130,2
4	tophole	152,1856
5	bside	217,408
6	mside	94,5
7	topsquare	130,4448
8	sidesquare	126
9	upsquare	228,2784
10	front	414,388
11	back	667,6
12	9-2	108,704
13	5+2-9	108,704
14	5-7	86,9632
15	surplus_int_h	18,5008
16	surplus_int_v	20,888
17	surplus_ext_h	19,554
18	surplus_ext_v	19,554



4 layers

Number of pieces	42
Number of surplus	36

Horizontal surface	7511,9856
Vertical Surface	49337,856

	Sholes_v	Sholes_h	Total	Quantity
1	1808,6896	1536,0688	2703,4048	6
Total	10852,1376	9216,4128	16220,4288	6

Total horizontal surface	Sh= 16728,3984
Total vertical surface	Sv= 60189,9936

3 layers

Number of pieces	30
Number of surplus	24

Horizontal surface	8592,528
Vertical Surface	37434,0336

	Sholes_v	Sholes_h	Total	Quantity
1	1808,6896	1536,0688	3344,7584	3
Total	5426,0688	4608,2064	10034,2752	3

Total horizontal surface	Sh= 13200,7344
Total vertical surface	Sv= 42860,1024

17.7 Log book / journal

Who
Kim
Yassin
Emma
Lucie
Everyone

Who	What	When	How long
Everyone	Opening EPS	08-02	2h
Kim	Analysing 2 articles given by supervisors (C16.2)	20-02	2h
Emma	Analysing 2 articles given by supervisors	21-02	2h
Lucie	Analysing 1 article given by the supervisors	22-02	2h
Everyone	Teambuilding	27-02	6h
Everyone	Teambuilding	28-02	6h
Everyone	Meeting	01-03	2h
Lucie	Gantt chart	04-03	2h
Yassine	Research of the species on the Vilanova's coast	15-02	4h
Kim	Research C16.1 Orientation on artificial reefs	14-02	2h
Yassine	General research about artificial reef's specifications	16-02	1h
Yassine	Determination of the specifics and parameters of artificial reef that aim to increase biodiversity	16-02	1h
Everyone	Meeting	14-02	2h
Kim	Research on materials	14-03	1h
Emma	Research of the characteristics of the species	14-03	2h
Yassine	Research about the SARTI company	14-03	2h
Yassine	Understanding of the database of the SARTI company	14-03	2h

Yassine	Meeting with SARTI	14-03	1h
Kim	idea generation	14-03	0,5h
Lucie	Research on other artificial reefs	20-03	1h
Lucie	Research on different companies creating 3D artificial reefs	20-03	1,5h
Everyone	Meeting	21-03	1h
Kim	idea generation (sketching)	22-03	1h
Lucie	Market research chapter (C 3.1)	22-03	1h
Lucie	Competitive research chapter (C 3.2)	22-03	2h
Yassine	Company chapter (C2.1)	22-03	1h
Yassine	Area chapter (C2.3)	22-03	1h
Emma	Spices chapter (C3.3)	23-03	1h
Kim	Stakeholder map	23-03	0,5h
Emma	Research methodology given by supervisors (AREIT)	23-03	1h
Emma	Design phase chapter (C4)	23-03	0,5h
Yassine	Research methodology given by supervisors (Current and geometry)	23-03	1h
Everyone	Brainstorming for ideas	23-03	3h
Emma	Method (plan of aproach) (C4.1)	23-03	1h
Everyone	Working on the project management presentation	26-03	2h
Kim	Idea generation (sketching)	27-03	1,5h
Emma	Idea generation chapter (C4.2)	27-03	0,5h
Everyone	Visit Universitat Politécnica de Catalunya	28-03	3h
Kim	Worked on midterm presentation	29-03	0,5h
Emma	Worked on midterm presentation	29-03	0,5h
Lucie	Worked on midterm presentation	29-03	0,5h
Yassine	Worked on midterm presentation	29-03	0.5h
Kim	Concept forming (sketching)	29-03	3h
Everyone	Midterm presentation	30-03	0,5h
Kim	Start 3D CAD model development	20-04	2h

Yassine	Understanding the AREIT article	22-04	4h
Lucie	AERIT spreadsheet / Calculations	23-04	3h
Emma	AERIT spreadsheet / Calculations	23-04	3h
Yassine	Verify the AREIT spreadsheet	23-04	0.5h
Kim	3D model development	25-04	1h
Everyone	Meeting	26-04	2h
Emma	Risk analysis task	26-04	1h
Yassine	Risk analysis task	26-04	1h
Kim	3D model development	06-05	1h
Everyone	Meeting	09-05	1h
Emma	Consultation Antonio Sánchez Egea	10-05	1h
Yassine	Develop a strategy to choose the values of the simulation	11-05	0.25h
Yassine	Current data readings (+300 values/+150graphs)	11-05	4h
Yassine	Statistic calculation about current data	11-05	0.5h
Emma	Calculation statics spreadsheet	11-05	2h
Lucie	Printing of 3D plastic pieces	11-05	6h
Kim	Adjusting 3D model	15-05	1h
Emma	Risk analysis chapter (C12.5)	15-05	0,5h
Lucie	Calculation (AREIT index)	16-05	3h
Everyone	Meeting	17-05	1,5h
Kim	Adjusting 3D model	17-05	1h
Emma	Meeting OBSEA	17-05	1h
Emma	Research OrcaFlex 11.3	17-05	1,5h
Emma	Simulations	18-05	2h
Kim	Design studies & team member introduction	23-05	3h
Emma	Team member introduction	23-05	0,5h
Yassine	Team member introduction	23-05	0.25h
Yassine	Choice of the current values of the simulation	23-05	0.5h
Kim	Presentation drawings	23-05	3h
Kim	3D models rendering	23-05	2h

Yassine	3D printing with concrete chapter (C3.5)	23-05	1h
Emma	Readjustment simulations	23-05	2h
Kim	Finalisation 3D models	24-05	4h
Yassine	What is AREIT? chapter (C12.2.1)	24-05	1.5h
Yassine	Other statistic calculations of the current values	24-05	0.5h
Kim	Technical drawings	24-05	1h
Kim	PCM drawings	24-05	0,75h
Kim	Eco Design chapter start	24-05	1,5h
Emma	Meeting OBSEA	24-05	1h
Lucie	Calculations (AREIT index) chapter (C 12.2)	24-05	3h
Lucie	Cost price chapter (C 12.1)	25-05	2h
Kim	Eco design chapter	25-05	2h
Emma	Simulations	25-05	1,5h
Yassine	Simulation chapter (C12.3)	25-05	2h
Kim	Load situation	26-05	1h
Kim			
Emma	Simulations chapter (C12.3)	27-05	2h
Yassine	Last modifications on the report	27-05	2h
Lucie	Requirement chapter (C 3.6)	27-05	1h
Emma	Simulations chapter (C12.3)	28-05	1h
Emma	Conclusion chapter (C14)	28-05	0,75h
Emma	Recommendations chapter (C15)	28-05	0,5h
Emma	Results chapter (C13)	28-05	0,5h
Everyone	Finalisation report	29-05	2h