# ELISE 3D - A DATABASE-DRIVEN ENGINEERING AND DESIGN TOOL

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## ABSTRACT

In order to realize completely new functional design approaches one has to deal with combinations of different geometries, materials and construction methods. The acquisition of the needed data for a totally new initial model is complex and therefore the design of new light structures is typically done by changing or optimizing existing solutions. In contrast, the new database-driven engineering and design tool ELiSE 3D draws on the shell design of high-strength, unicellular marine organisms such as diatoms and radiolaria to provide design concepts for large scale technical lightweight structures. Since about 100.000 different species with different light structure geometries are known, a systematic use of this pool of potentially technically usable structures has a high potential to design and improve lightweight constructions in different industries. Here we show, that unique design solutions can be found efficiently and integrated to a consistent workflow.

*Keywords: lightweight construction, biomimetics, database, marine plankton, functional similarity search*

## 1 INTRODUCTION

The development of a functional and light structures is typically done by changing or optimizing existing solutions. Such designs are thus characterized by the initial solution and therefore offer little scope for completely new, highly efficient solutions. For the realization of completely new functional design approaches, different geometries, materials and construction methods are necessary.

Current commercial optimization tools to create lightweight structures typically use the stress distribution within a given space in order to differentiate between necessary and useless material [1]. This leads to frameworks, whose intricateness typically depends on element numbers and thus spatial resolution.

Although these methods lead to considerable improvements of technical lightweight structures, they often do not meet the needs of designers and engineers, because they generate only a small fraction of the possible efficient solutions. Because lightweight problems can be solved by many different geometries, it would be helpful to have access to diverse lightweight principles as starting points to the creation of new lightweight designs.

It is known for several years that plankton shells are highly developed and stable lightweight constructions and often develop extraordinary designs, which are often unfamiliar to the human eye [2]. During many million years of evolution, uncountable optimization steps happened. About 100.000 different species with different light structure geometries are known [3]. A systematic use of this pool of potentially technically usable structures has a high potential, as these geometries can be used as templates for new technical design solutions [4].

Diatoms are microscopic algae with an average size of about 2µm up to more than 1mm, which float in the photic zone of the oceans [5]. They form the main component of the phytoplankton and are responsible for most of the oceanic primary production. Diatoms are, in terms of biodiversity and biomass, the most important group of unicellular microalgae, and often dominate phytoplankton composition in the oceans and in many freshwater ecosystems. The basic structure of a diatom siliceous exoskeleton (frustule) resembles a pillbox made of two shells. Diatoms have to protect themselves from a wide range of predators such as copepods and krill [6], but cannot be heavily armored, as they can only survive at depths which provide enough light. This compromise between light weight and enormous strength is reflected in a very large variety within the diatoms [7].

Radiolarians are amoeboid protozoa that produce intricate mineral skeletons. They occur exclusively in the oceans. Like diatoms, they face the dilemma of having to protect themselves against mechanical challenges but need to do this using stable lightweight constructions, because they live preferentially in the upper layers of the water column. The main reason is that nutrient availability decreases rapidly with water depth. In contrast to the box-like silica structures of diatoms, whose inner space is largely empty, radiolaria seem to be completely free in the design of their exoskeletons (shells). Therefore, both hollow shells and geometries filled with complex frameworks exist among radiolarian species.

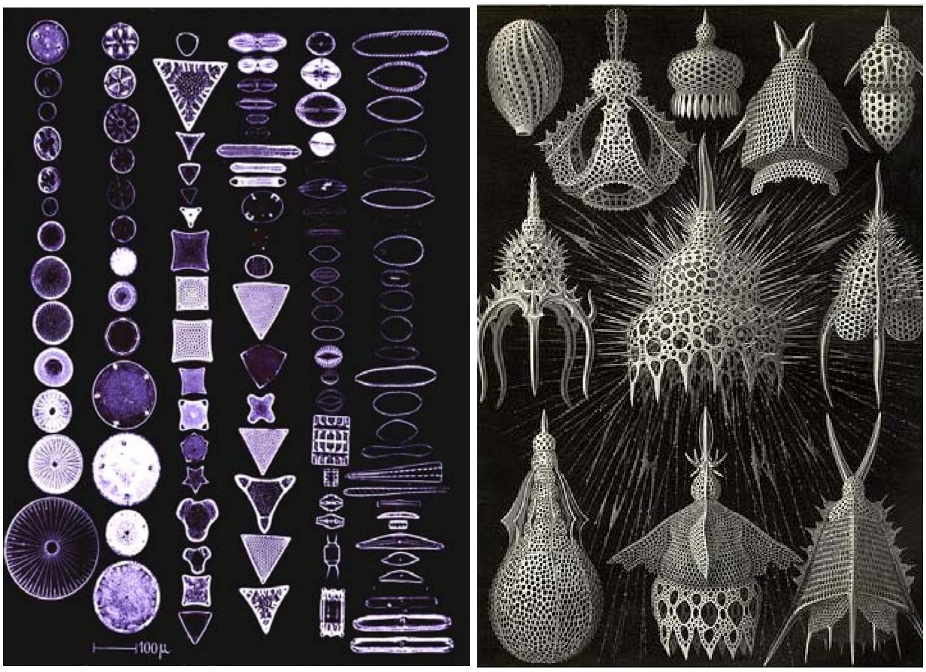



**Fig. 1: Diatoms in different forms and sizes (left [8]) and radiolarian (right [9])**

Within the procedure ELiSE (Evolutionary Light Structure Engineering), pre-optimized lightweight structures of plankton shells are systematically used, allowing the development of various new lightweight solutions for each specific technical problem.

This paper presents the further development of the procedure ELiSE to an industry-related design tool realized within an online database-driven engineering and design tool called ELiSE 3D.

## 2 ELISE PROCEDURE

The procedure ELiSE is a biomimetic method to improve lightweight structures by systematic use of different pre-optimized structures of plankton organisms. Also new and uncommon designs can be achieved easily.
Lightweight construction for specific technical problems can often be solved by very different geometries. This situation can be described by the term "optimization mountains" and shows a difficulty of linear optimization methods such as Computer Aided Optimization (CAO) and Soft Kill Option (SKO) or topology and shape optimization (Fig. 2).

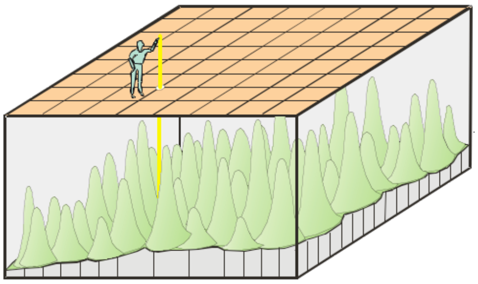


**Fig. 2: Multiple peaks in optimization mountains (Rechenberg, Shanghai lecture)**

With the use of iterative, linear optimization procedures often only a local, but not necessarily the global optimum is reached. The procedure ELiSE uses pre-optimized lightweight structures, allowing effective and rapid development of various new lightweight solutions. The technical realization is supported by basic research in the fields of plankton evolution, plankton biomechanics, diatoms taxonomy and genetic algorithms ([10], [11], Planktontech[1]). The procedure ELiSE is based on findings on basic research, which show that the shells of plankton organisms are adapted to different mechanical loads by feeding tools. The innovation compared to other approaches is that concrete lightweight geometries are extracted. This leads to diverse, fast and effective solutions. The scaling of microscopic lightweight structures is possible due to the fact that both, material cross-section and surface pressure are scaled by the square of the linear scale. Therefore fantastic lightweight structures from the microcosm can be transferred for almost any technical application.

As shown in Fig. 3 the procedure starts with a screening phase in which biological models are scanned with regard to similarity with the projected geometry and solution of the technical problem. After that the structures are constructed and their performance is analyzed using standard construction software and finite element (FE) methods and loadcases typical for the structures which are relevant for the technical structure. Due to the results of this analysis one can assert whether the model is a promising design proposal or not. In a third phase of the ELiSE procedure the selected biological models are simplified due to technical (e.g. constructive) aspects. Details and unloaded sections can be removed. In phase four optimization tools are applied. Therefore parameterization is used as well as genetic algorithms and topology optimizing tools. Aspects concerning manufacturing take place in a last step.

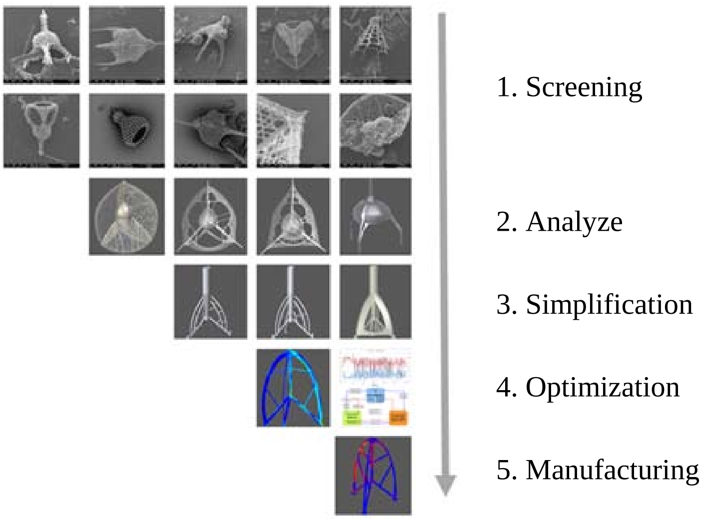



**Fig. 3: Schematic figure of the procedure ELiSE**

[1] www.planktontech.de

## 3 EXAMPLE: OFFSHORE FOUNDATION

An actual project (OFE) deals with offshore foundations for wind power plants [12]. Its goal is to reduce weight and costs by developing a foundation based on the procedure ELiSE. The actual foundation is designed as a tripod with a complete weight of about 770t. It's height is about 48m, and it is designed for a water depth of about 30m.

All efforts of designing a new geometry with state of the art optimizing tools ended in cross beam structures, which only can be build in an expensive way. Varying the tube thickness and contact points of the current tripod design by genetic optimization algorithms could minimize its weight insignificantly [13].

At this stage several suitable species were selected from the radiolarian pool (Fig. 4). Because the biological models obviously aren't designed to carry a wind power plant, all models need to be analyzed using FE methods. Therefore all models were constructed in CAD and abstracted according to the technical load case of the foundation [14].

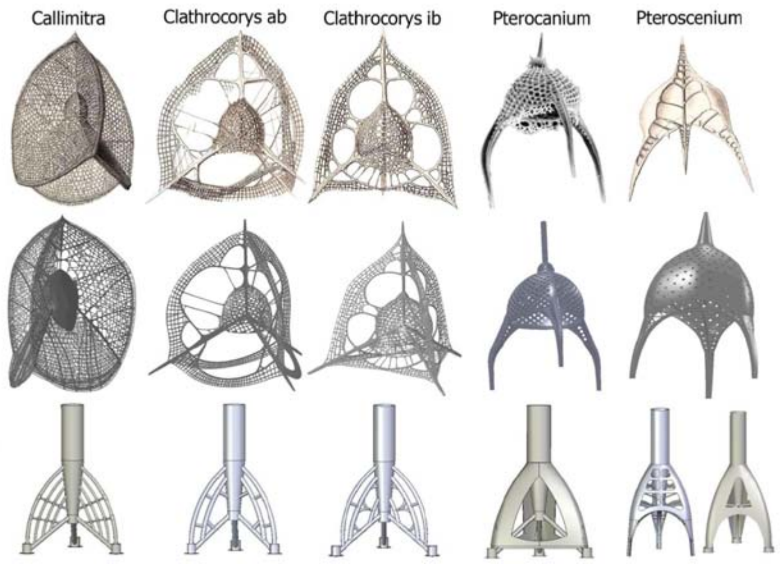
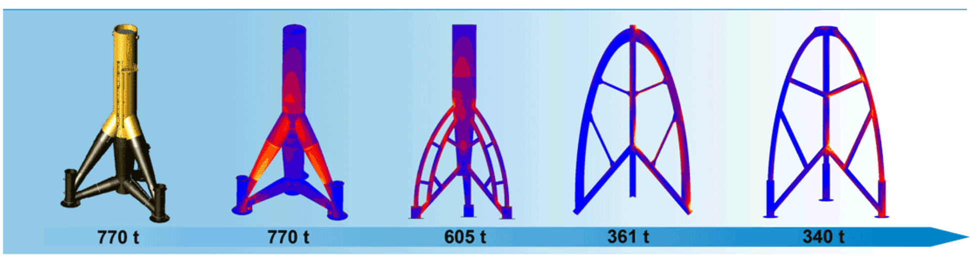
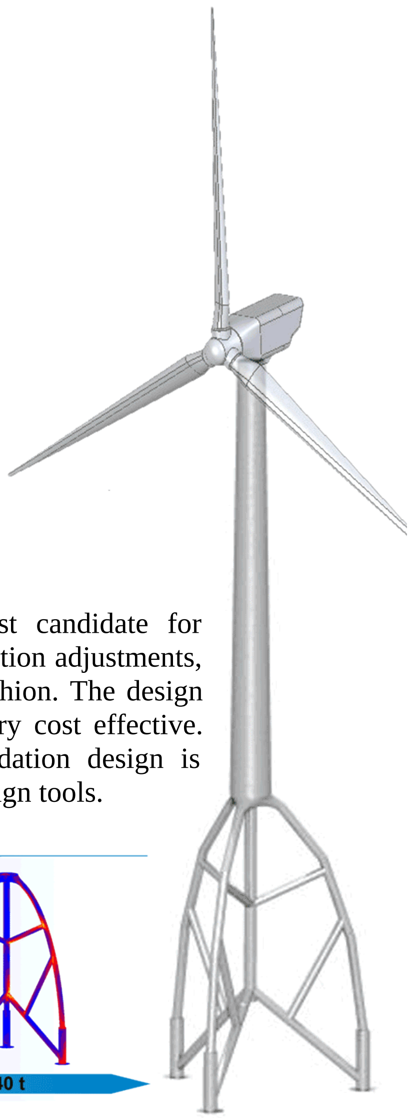



**Fig. 4: Overview of different design proposals and CAD abstraction [14]**

The results of the calculations selected *Clatrocorys* as the best candidate for optimization. After optimization of the structure and relevant production adjustments, the offshore foundation could be designed in a completely new fashion. The design proposal only makes use of standard pipe diameters which are very cost effective. The overall weight could be decreased to 400t. The new foundation design is absolutely unique and can't be developed with actual engineering design tools.



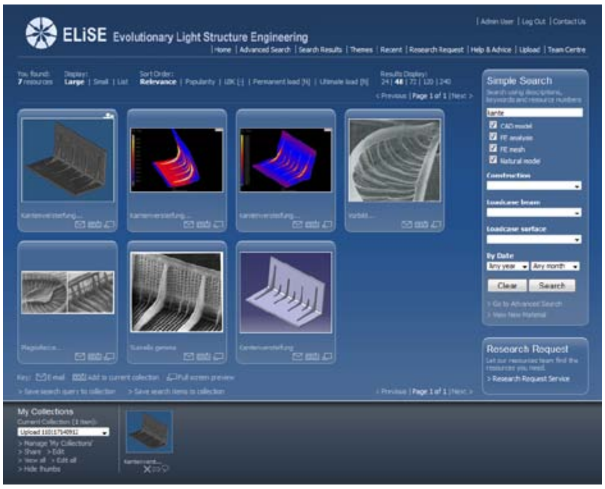



# 4 LIGHTWEIGHT DATABASE ELISE 3D

An engineering problem with no unique solution is in general a design problem. When using marine plankton organisms as templates for a new design, specific expert knowledge is needed. Up to now, a large team of biologists and engineers and relatively much time is required to develop new technical structures using the ELiSE method.

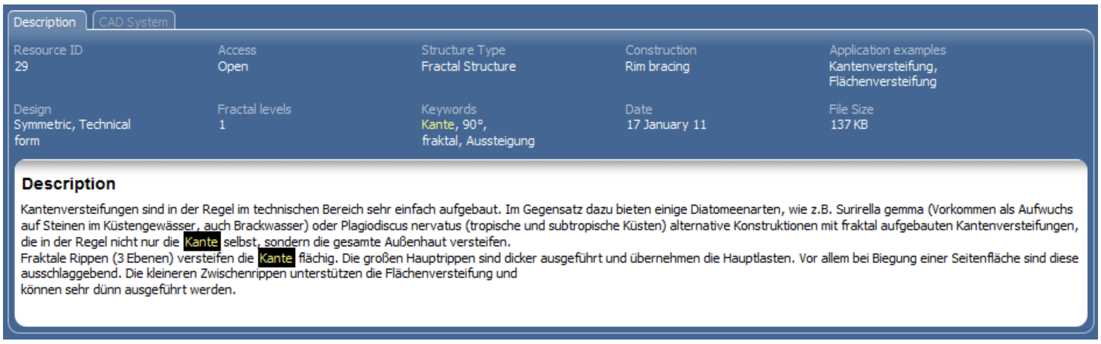
The goal of the ELiSE 3D lightweight database is to combine these expertises in one handsome engineering and design tool. Engineers and designers should be able to use this vast pool of ideas without profound biological knowledge about plankton organisms. One should have the opportunity to use the latest scientific findings from research for engineering and design problems. Innovative lightweight structures and original design components are stored, categorized and easy to integrate into the design process.

According to the workflow of engineers, the stored data includes microscopy images such as SEM (Scanning electron microscopy), and CLSM (Confocal laser scanning microscopy). With this information the original biological structures can be examined. Linked with the biology models abstracted CAD models in different formats can be supplied for 3D-view and directly imported into any CAD program. Furthermore FE analyses with different material properties are stored for several standard load cases, allowing the user to understand the behavior of the structures and to compare structures according to their lightweight potential. So all information in the database is in relation with each other.



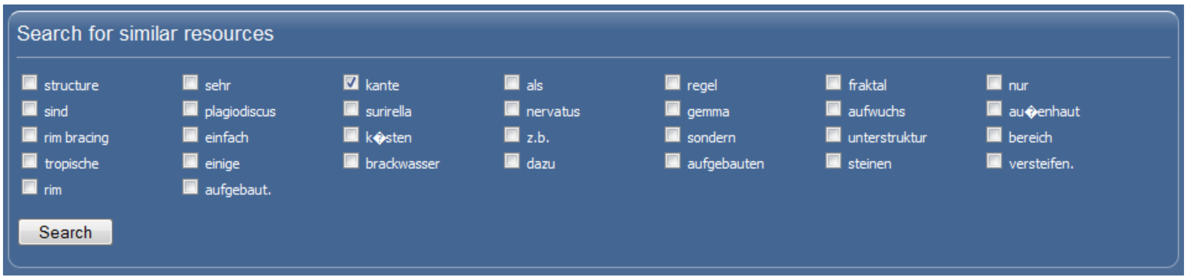

(1)


(2)




(3)


**(4)**




**(5)**

**Fig. 5: Overview (1), download (2), description (3), related resources(4) and similar resources (5) in ELiSE 3D**

When search for new lightweight structures a metadata driven keyword system is used to obtain a powerful tool. General information is stored within each item in the database.
Among others, these information are:

- Title
- Description
- Structure Type (e.g. fractal are large structures)
- Construction (e.g. beam structure, honeycomb structure, rim bracing)
- Application examples
- Geometrical shape (divided into 2D and 3D aspects)
- Design (e.g. curved surfaces, organic form, symmetric, round elements)
- Fractal levels
- Keywords

With these information a general lookup for interesting items can be achieved. Similar items can be found and compared. Linked together with every biology model a CAD part is stored in the database. In addition to the general information, each item is provided with, a CAD item is described more detailed. Information based on the technical background of CAD tools is stored like:

- CAD system (e.g. CATIA, ProE)
- Amount of parameters within the part
- Construction method (e.g. surface model, volume model)
- Comment

The user can have a 3D preview of the parts with an integrated viewer. So the parts can be examined from each side and can be zoomed to details. CAD items and biology models can also be used from designers to gain new constructional forms. New ideas of functional designs can therefore be achieved very effective by searching terms like for example "organic form" or "symmetrical shell enforcements".

The comparison of multiple items according to their lightweight potential is necessary to find the best solution with reference to a given design problem. Therefore geometric characteristics and describing metadata is not sufficient. In addition the mechanic behavior of the structure has to be considered. It is necessary to calculate stresses and displacements of the structures.

To ensure comparability of the structures within the database, the structures are assigned to different categories. These categories depend on their geometric design like beam structures, shell structures and volume components. If possible, the geometric properties like length, width are normalized.

The FE calculations are based on basic standard load cases (Fig. 6) according to the categories of the structures. For that reason beam structures are calculated as follows:

- Bending force at free end
- Bending force in the middle
- Compressive force at free end
- Compressive force at both ends
- Area load

In parallel, surface structures are calculated along these lines:

- Linear load in the middle, parallel to restraint
- Surface load
- Compressive force orthogonal to restraint
- Compressive force parallel to restraint

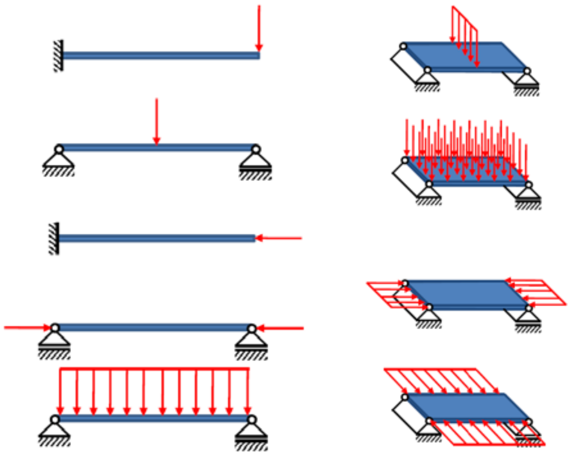


**Fig. 6: Overview of load cases of beam structures (left) and surface structures (right)**

By contrast to these two structure types, volume components can be designed very differently. Therefore, it is difficult to define standard load cases. Thus, the database provides a special load case for each volume component. As a result it is only possible to compare volume components of an similar design and function.

While not all structures can be of the same size and dimension, it is crucial to define a parameter (LBK) independent to material, dimension and load case [15]. This parameter is used to evaluate and compare items within the database. It is defined as the ratio between the ultimate load ($F_G$) and the dead weight ($F_E$) of the unloaded structure:

$$LBK = F_G / F_E \quad (1)$$

To determine the ultimate load of a structure, it is loaded with a linearly increasing force until plastic displacement begins. This criterion is used as a failure criterion to calculated the maximum absorbed force. The dead weight of a structure is calculated from the material density, volume and gravity acceleration.

The larger the LBK, the better the structure is suitable for the selected load case with respect to its lightweight potential.

## 5 FUNCTIONAL SIMILARITY SEARCH WITHIN THE DATABASE

As described before, the lookup of structures can be achieved by using meta data and parameters. An engineer often has very specific load cases and therefore specific load paths within a restrictive design space. Therefore it is reasonable to use this boundary conditions to search for suitable biological archetypes.
In contrast to known similarity searches with 3d data, the use of the discrete forms and shapes of the structures isn't purposeful because gaining new lightweight structures by new forms is the basic idea behind ELiSE.

As a technical structure can be defined by its capacity to support load-paths from in- and output areas, it is useful to first consider the structure in a very abstract way. Assuming that the technical component (which should be optimized) is a black box, it is used to redirect forces of (multiple) points to other points under certain restrictions. Therefore it is possible to describe the function of a technical structure by a spatial description of the points of load in- and output.

The features of the functional similarity search for the lightweight database are therefore not the geometric data itself but rather the functional inputs and outputs of the structure (see Figure 7). It is therefore possible to search for functional similar structures with different forms (e.g. a biological model with similar function like the technical problem).

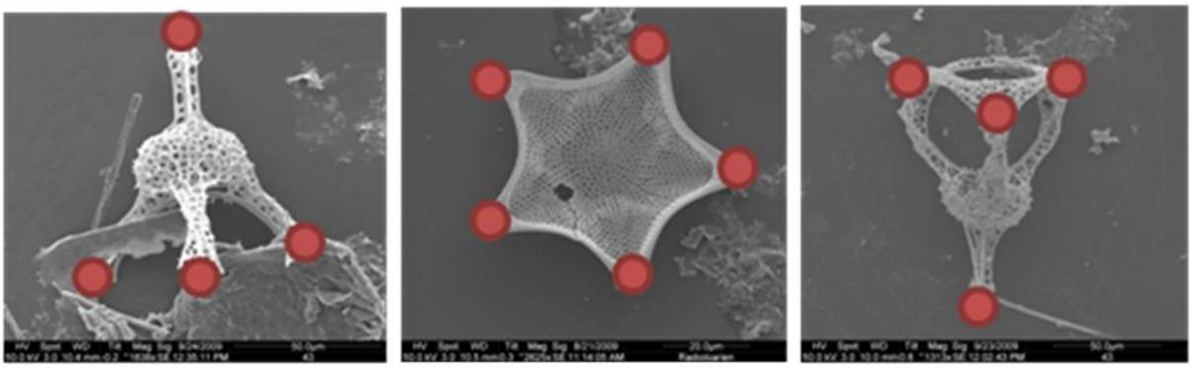


**Fig. 7: Functional points of diatom and radiolarian shells**

Within the ELiSE 3D database several algorithms are used to assure invariance in respect of translation, rotation and mirroring. The engineer has to put in the coordinates (x,y,z) of the function points of his technical problem and the database can search for similar functional biological models.

The results of the implemented nearest-neighbor search algorithm can then be visually prepared with the help of multidimensional scaling (MDS). With MDS it is possible to generate a two-dimensional map (see Fig. 8) on which the individual structures are arranged corresponding to their similarity. Functionally similar structures are grouped and closer together than functionally dissimilar structures.

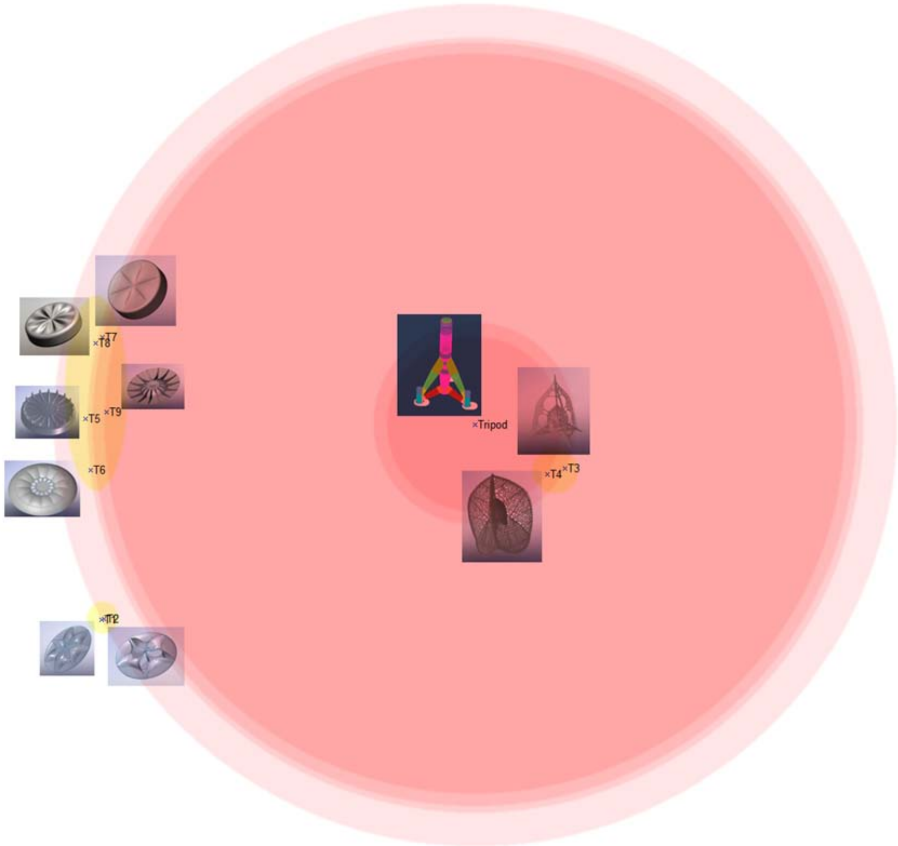



**Fig. 8: Functional similarity map shows similarity of radiolaria and tripod (middle) and clusters of similar diatom shells (left)**

## 6 DISCUSSION

Compared with other engineering design tools like topology optimization tools (Altair Optistruct, SKO, etc.), ELiSE 3D it is quite inimitable. Mathematic algorithms, like most other design tools make use of, mostly suggest lattice structures. In contrast really innovative, different and efficient solutions can be found in nature. However ELiSE 3D needs huge amount of preliminary work to be as universal as topology optimizing tools. There have to be sufficient biological structures set up in the database as well as abstracted CAD parts and finite element analysis to cover a broader range of technical applications.

Assuming a sufficient filled ELiSE 3D database, time to market can be very short due to the expert-like information stored in the database. Future developments of the ELiSE 3D database should therefore focus on manufacturing aspects and suggestion of preferred materials for each structure.

In contrast to topology optimizing software the result of an ELiSE 3D optimization is a full completed (parametrical) CAD model which can be quickly adapted to the user requirements. The result of a topology optimization tool like Optistruct is a finite element structure, whose transformation to a CAD model takes a long time. Furthermore the results of 3d topology optimization tools mostly are castings which are limited in manufacturability.

The aesthetics and design aspects of natural lightweight structures generated with ELiSE 3D cannot be produced with a mathematic tool yet. This can be an advantage in terms of brand protection and recognition value of these biomimetic structures.

ELiSE 3D can be used universally by nearly any branch of industry. Automotive construction engineers as well as aerospace engineers, architects and designers can benefit from any number of sandwich constructions, surface structures, beam structures and just as much from new ideas and impressions of shape of products. ELiSE 3D is an innovative new approach which makes biomimetic developments accessible to engineers and designers without having any knowledge or background regarding biology or biomimetics.

Finally, bionic structures can be very interesting for industry regarding marketing aspects. As shown in the example OFE, structures developed with ELiSE often are more organic than common technical structures and therefore quite unique and memorable. An advertising campaign can use this aspect as a good selling point. On the other side these structures are typically more complex than normal technical structures. Therefore, if efficient production methods (e.g. casting) are not available, the realization of very effective bionic lightweight structures may be more expensive than are standard solutions. Thus, current research on new techniques which support the production of complex geometries thereby promote the application of the ELiSE 3D database.

## 7 CONCLUSION

The new design of an offshore foundation shows how marine plankton organism can be used as archetype to generate innovative lightweight structures with the procedure ELiSE. In combination with the presented database ELiSE 3D the procedure can be even more efficient. Due to prepared, categorized information and a new developed functional similarity search engine it can be an attractive tool for engineers and designers, supporting everyday work and giving new ideas in structural design. Assuming sufficient biological structures and abstracted models in the database, ELiSE 3D is a serious alternative to common topology optimization tools.

Future developments of the ELiSE 3D database should focus on manufacturing aspects, as most biological models are of a certain complexity. Suggestions of meaningful manufacturing methods of each structure will be a helpful feature. Furthermore a suggestion of the recommended material could be very interesting. The functional similarity search algorithms should be extended to support functional areas as well. It will therefore be necessary to do research on different distance measure methods and clustering algorithms to maintain the invariance in respect of translation, rotation and mirroring.

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