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Biomimicry in the Classroom

How Biomimicry can be integrated in the Dutch curriculum

Matthijs Roobeek



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Research Report BiomimicryNL

Bio Inspired Innovation, Utrecht University

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Minor Research Project, January-August 2019

Abstract

Biomimicry as a contextual learning method has the potential to be used in education for integration of skill-training across the beta sciences. The *Nationaal Expertisecentrum Leerplanontwikkeling* (SLO), the expertise centre for educational innovation, acknowledges there is a need for innovation in the system of Dutch secondary education. The organization is currently working on a redesign of the educational setting. This redesign could mean there is more room for STEM-focused education. To stimulate this movement, biomimicry as a contextual design method could have a great impact, but in what way biomimicry should be used in education is still widely unknown. This study aimed to identify what role biomimicry can play to close the gaps that teachers identify between the current educational situation and the ideal educational situation. The gaps were identified by performing a need analysis and are used to formulate criteria for new teaching material about biomimicry. The developed materials were evaluated and analysed, which together with the needs analysis form the basis of an advisory report to BiomimicryNL, which aims towards the inclusion of biomimicry in secondary education. This study found that biomimicry has the potential to be implemented in secondary education, concluding that biomimicry material creates value by closely adhering to new ways of teaching. The intrinsic value of biomimicry ensures that material about biomimicry enables student-centred learning which sparkles students' curiosity, allow active learning and integrate this in interdisciplinary project-based material that fully covers the most needed 21st century skills.

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Laymen's Summary

Biomimicry is a design method that uses knowledge from nature as inspiration for sustainable design. It is an interdisciplinary approach that brings together nature, biology, design and technology. The method has the following setup; first a design problem is identified, then the functions of that design are identified, after which the link is made to how those functions are executed by organisms in nature. Biomimicry has the potential to be used for more than design alone, possibly because of its specific setup.

One of its potentials lies in education. The *Nationaal Expertisecentrum Leerplanontwikkeling* (SLO) is the most influential Dutch expertise centre for educational innovation. They are constantly working on evaluating and redesigning the educational system. This is very important in the always-changing society. It is interesting to investigate where biomimicry could have an impact on the innovation of the Dutch secondary education. This study aimed to identify the gaps that teachers experience between the current educational situation and the ideal situation, and aimed to investigate how biomimicry could play a role in fulfilling the needs to fill these gaps. The study follows the structure of educational design research. By conducting a needs analysis, which is done by interviewing teachers and experts in nature education, the needs in the educational setting are defined. Then, the relation between these needs and the values of biomimicry are analysed. A set of criteria are set up based on these needs and values, which form the basis of new teaching material about biomimicry. Two courses were developed, 'Marvellous Models' and 'Packaging'. These courses were tested in the *onderbouw* of high schools, after which an evaluation took place by means of interviewing teachers and conducting student surveys.

This study found that biomimicry has great potential to be implemented in secondary education. The important suggestion is to adhere to new ways of teaching as much as possible. Teachers indicate they want materials that enable student-centred learning, which sparkles students' curiosity, allow active learning, and integrate this in interdisciplinary project-based material that fully cover the most needed 21st century skills. The 21st century skills are defined as soft skills that students need to acquire to be fully prepared for a job in the 21st century.

This is exactly where the intrinsic value of biomimicry lies, according to the results of the needs analysis. The results of the evaluations, together with the needs analysis, form this research report, which also acts as an *advisory* report to BiomimicryNL to aid them in their project BioLearn. The most important recommendations are:

- Biomimicry material needs to:
    - Enable student-centred learning sparkling students' curiosity
    - Integrate active learning in interdisciplinary project-based topics
    - Integrate all 21st century skills
- Biomimicry can also be introduced as 'bio inspired' or 'inspired by nature'
- Reach out to teachers online via websites promoting or offering teaching material

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Introduction

This research report is the result of a 6-month internship project at BiomimicryNL. BiomimicryNL is a non-profit organization focused on helping companies and institutions to apply biomimicry on product, process and system level. The goal of BiomimicryNL is to use biomimicry as a tool to accelerate the transition to a circular economy. For 6 months I was an intern at BiomimicryNL and participated in an ongoing international education project: BioLearn.

BioLearn

BiomimicryNL is a part of a consortium of partners that work in an EU Erasmus+ project called BioLearn. The main goal of the project is to provide teaching materials and training on the topic of biomimicry for STEM educators across the European Union. The project is set up under the assumption that innovation inspired by the natural world is one of society's driving scientific and economic forces today. They argue that since educational and research institutions have picked up and integrated biomimicry across research and teaching in design related fields, there is a need for biomimicry related materials to prepare young people for college and career and to foster a more STEM-educated society.

Since BiomimicryNL is one of the organizations with the most expertise in the biomimicry approach, the organization also serves a guiding role in which it shares its knowledge whilst also being open for new ideas. As an extra goal set itself for this project, BiomimicryNL takes it a step further by investigating how to properly integrate the materials created into Dutch secondary education as well as how to inspire teachers to use biomimicry as a design method in their classes. This report, which can be seen as a summary of my project at BiomimicryNL, therefore serves to investigate the two goals: on the one hand to provide crucial information to be used in the BioLearn project, on the other hand to advise BiomimicryNL on how to implement material and how to inspire teachers.

Biomimicry as a design method

The term biomimicry was first used by Janine Benyus in her book 'Biomimicry: Innovation Inspired by Nature'.[1] Biomimicry, from the Greek words 'bios' meaning life, and 'mimesis' meaning to imitate, is using knowledge from nature as inspiration for sustainable design. It is an interdisciplinary approach that brings together nature, biology, design and technology. The theory contains of three essential elements: Ethos, (Re)connect and Emulate.[2] The ethos element inspires the ethical intentions and explains the underlying philosophy of why biomimicry should be practiced. According to biomimicry, nature should be respected. The reconnect element brings up the understanding that we, as humans, are nature. According to Benyus, humanity has separated nature from themselves, and nature and humanity are now often seen as separate parts. It is the goal of biomimicry to reunite these two. The emulate

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element brings out biomimicry at its most practical: it can be used to guide seeking sustainable solutions by understanding principles and strategies from nature.

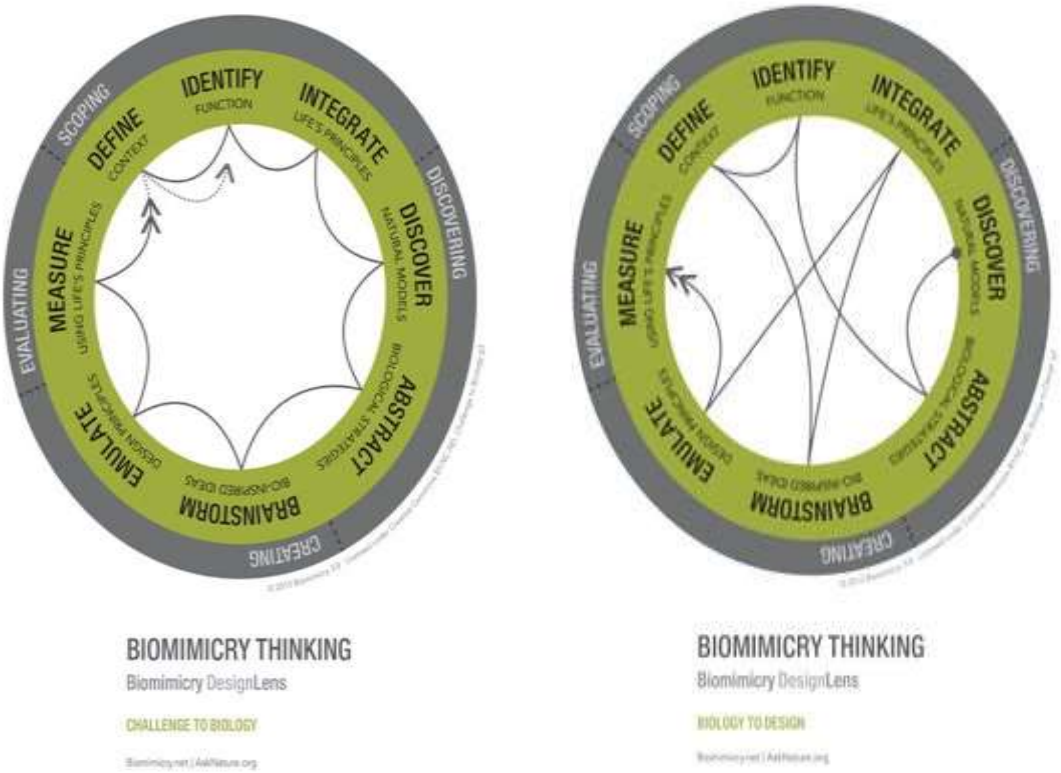
In design, biomimicry can help with providing new insights. The Biomimicry 3.8 Institute has provided several working tools that designers could use, called the Biomimicry DesignLens.[3] Biomimicry can be used on three different levels; to design products, processes, or complete systems. A prominent feature of design using biomimicry is to evaluate the design using biomimicry's nature's principles. These are guidelines indicating how designing is done in nature. These features can also indicate how sustainable designs are and what needs to be done to make a design more sustainable.



Nature's principles by Biomimicry 3.8

Designing using biomimicry forces the designer to identify the functions of a product, process or system. Then these functions are connected to natural models; they explain how functions are executed in processes or by organisms in nature. This feature allows for two possible routes for designing. It is possible to start with a problem, link to functions, and then consult nature. Additionally, one can start by studying nature's organisms, processes, or systems, and identify functions from there.

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Two possible routes for using biomimicry in design: From challenge to biology and from biology to design.

Biomimicry in education

Biomimicry as a contextual learning method has the potential to be used in education for integration of skill-training across the beta sciences.[4] Biomimetic projects encourage students to acquire both knowledge and (soft) skills while also learning to think in a sustainable and circular way. This contextual method could possibly be applied to many beta-sciences. So far, not many examples can be found where biomimicry is used in (secondary) education.[5] Next to this, there is a possible gap between how current education performs and what the curriculum prescribes how the ideal situation should be. This gap could be filled by using biomimicry as a design method. The need for implementation of 21st century skills in education might play a key role in this connection. However, these relations and possibilities have not been studied yet. Therefore, in order to create a *possibility* for biomimicry to fit into Dutch education, there is a need to study *how* biomimicry could be implemented before it can be fully operated. This study will focus on what is needed to implement biomimicry as a learning method into the Dutch curriculum. To what extent biomimicry connects to currently existing features of the Dutch curriculum is therefore important. More importantly, it is relevant to study what features of the re-innovated curriculum can be linked to biomimicry as a learning method. Next to this,

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biomimicry can be used as a tool to help integrate and stipulate learning about all sciences, such as math and physics.

This study will have as its key focus to outline how biomimicry can fit into the process of how teachers design their classes. The structure of this study will follow that of educational design research, for which a needs analysis was done by conducting interviews after which a test course will be designed which is evaluated and possibly re-designed. The research approach and method are specified in the methods section. Whilst the evaluations of the materials directly cover the work tasks of the BioLearn project, the outcomes of the needs analysis, testing and evaluation altogether are summarized at the end and are used as an advisory report for BiomimicryNL.

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Research Questions

Main question

In what way can biomimicry, as a design approach, be productively used to support STEM-education at all levels of the *onderbouw* in secondary education of the Netherlands?

Sub questions (From needs analysis and literature research)

There are questions that need to be answered before the main research question can be answered. First are the questions that can be answered with the contextual inquiry and literature research. Here, I focus on Dutch secondary education in specific cases, as the information is gathered from interviews. But those results are supported by literature which may also give an indication of the Dutch secondary education as a whole:

- What didactic theories are currently used in STEM-subjects in Dutch secondary education?
- What are the developments around the learning goals of STEM-subjects in Dutch secondary education?
- Which aspects of biomimicry provide a relevant connection to the learning goals of STEM-subjects in Dutch secondary education?

Sub-questions (from needs analysis and intervention & evaluation)

To examine specific examples of how biomimicry could be integrated, these questions will be answered by doing qualitative research:

- What are the gaps between the ideal situation and the current situation of education, as identified by STEM-subject teachers?
- How can the to-be-created biomimicry courses fit into these identified gaps?

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Methods

Educational Design Research

This study follows the structure of design research as defined by Van den Akker in 1999.[6] Design research is characterized by a process oriented, cyclic approach of designing an intervention in the real world. The process starts with identifying a problem or gap between the ideal and real situation, where intervention is needed to fill that gap. This type of research is therefore very often used in educational fields, as this fields requires regular evaluation and reiterations of educational designs. In educational design research, designing a solution for an educational issue is central for the research process.[7] Before a design can be made, a needs analysis is conducted to see what the context is and to identify the margins of the gap. The whole study design is illustrated in Figure 1.

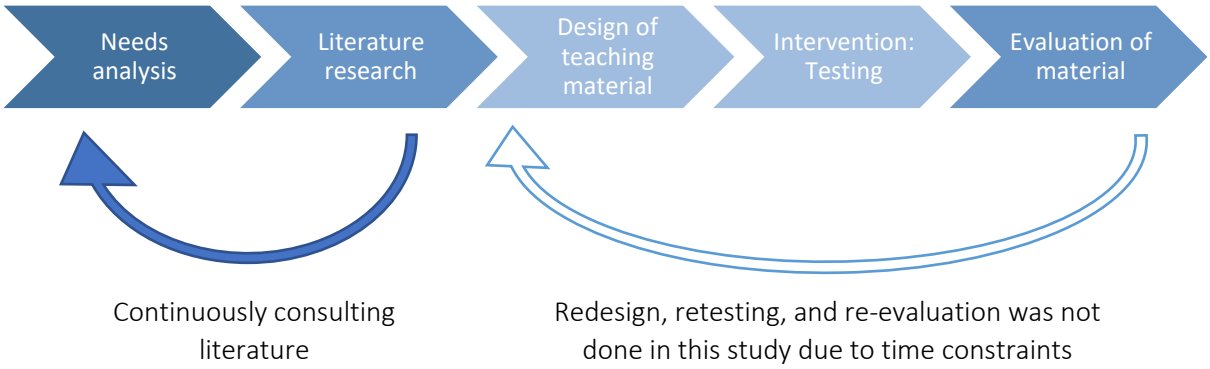


Figure 1: The study design

Needs analysis: Interviews

The needs analysis is conducted to identify the boundaries of the problem and the prerequisites of the intervention. The key focus of this research is to investigate what the current situations are and what the future situation will be. Only then can be known how biomimicry can be integrated in these situations, as a tool to fill the gap. To investigate this gap and the possibilities for biomimicry, a needs analysis by means of semi-structured interviews is conducted. The participants of the needs analysis can be categorized into two groups:

- High school teachers; they are the key group to implement the design in the real world, as they are the ones to make a difference in how classes are taught. The interviews with this group are also used to identify the context: to see how their classes are structured, how much they feel the need for new teaching materials, and how they would see biomimicry fit in their classroom. When referring to the methods and results of this case study, the participants in this group will from now on be simplified to ‘teachers’.

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- Experts at organizations/institutes working with biomimicry or biology in educational settings; they can be used as examples and provide guidelines for how biomimicry classes should look like. They know what works and what does not work. They also know the best ways to implement new rules, educational methods, and curriculum changes into classes that are fit for the educational system. Furthermore, it is relevant for BiomimicryNL to investigate how those organizations work with current school material about biomimicry. For the rest of this report the participants in this group will be referred to as the experts.

The decision has been made to only interview people that are familiar with the concept of biomimicry. In this way, all interviewees are better able to form an opinion about the implementation of biomimicry in education and long explanations or introductory courses on biomimicry are avoided. Subjects were gathered using the network of BiomimicryNL and from this seven people were interviewed: 4 teachers and 3 experts. Professionals working with educational innovation are important to investigate what can be expected to change in the curriculum in the following years. I followed a semi-structural format during the interviews, having identified key topics to discuss with questions related to these topics beforehand whilst also allowing new ideas to be brought up as a result of the interviewee's answers.[8] The format for the interview is given in Appendix A.

Table 1: Information about participants of the needs analysis

Participants needs analysis	
4 teachers • Biology (3), Science and Nature (1), Life & Technology (1) • *Onderbouw (3) bovenbouw (2)* • All levels	3 experts • Nature education (2) • Teaching material development (1)

The interviews are manually transcribed. The data is then analysed with the structure of a thematic content analysis using NVivo (a Computer Assisted Qualitative Data Analysis [CAQDAS] package). Following this approach, relevant parts are coded in three phases: open coding, axial coding, and selective coding. After relationships between codes are identified, overlapping themes are determined which provide the base for the content of advisory report.

Literature review (background)

A literature review will be conducted to gather knowledge about the background of the Dutch educational system and the innovation of the curriculum, 21st century skills and biomimicry. The literature reviewed is tailored to the outcomes of the needs analysis. The interviews indicate focus points, which the literature can provide more information about. For this review, peer-reviewed articles are used next to institutional reports and websites. For most articles, Google Scholar is be used. As the

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format of educational design research allows for cyclic research processes, the literature is repeatedly consulted and the review is continuously updated.

Design of teaching materials

The coded themes gathered from the interviews provide valuable information for the design of the biomimicry courses. The outcome is transformed into a list of criteria that can be used to develop new biomimicry courses. BiomimicryNL developed two models intended as part of the BioLearn project, these courses are used as design for this study. The criteria from the needs analysis are used as guidelines but the focus of the courses is still to fit into the needs of the BioLearn project. The courses are called *meesterlijke modellen* ('Marvellous Models') and *verpakkingen* ('Packaging').

Intervention: Testing & evaluation

The created courses were tested by 3 high school teachers. Participants for the testing were gathered via the networks of BiomimicryNL and UTalent. The participants for the testing phase were different teachers than those interviewed for the needs analysis. This prevents situations where teachers evaluate conforming the structure of the interview and therefore possibly acquire one-sided views.

See Table 2 for information about where the courses were tested. The course 'Marvellous Models' was tested twice: once with a biology class and once with a science class. The course 'Packaging' was also tested twice; once with the previously mentioned science class and once with a NaSk-class, which is the combination of physics and chemistry.

Table 2: Information about the tests

Test number	Course tested	Type of education system	Level & Year	Subject	Amount of students	Duration of test
1	*Marvellous models*	Regular	VWO3	Biology	18	2x50min
2	*Packaging*	Regular	HAVO3/ VWO3	NaSk	27	2x50min
3	*Marvellous models*	Special*	*	Science	9	60+75 min
4	*Packaging*	Special*	*	Science	8	60+75 min

**small scaled education system with all levels and all years of onderbouw in one class*

These different classes were chosen because it allows to study the multidisciplinary potential of biomimicry. Since biomimicry can be used in many different contexts, it could possibly be taught in multiple school subjects, like biology, math, or physics. In the evaluation with the teachers, it is asked whether they think biomimicry classes

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should only be restricted to biology, or be extended from biology-only to science-broad education. Science is a subject where students get topic-based classes within a broad range of science fields. It is therefore also interesting to see how biomimicry fits into such multidisciplinary and topic-based classes. This could also answer the research question; whether biomimicry can support integration of disciplines via STEM education.

The evaluations are built up by two components: evaluation interviews for teachers and small surveys for students. After each class, an interview with the teachers about the process and content of the course takes place. The interview focuses on the criteria and prerequisites established by the needs analysis, but also allows for the teachers to put forward important evaluation points themselves. Next to this, the teachers are asked to score to what extent the courses cover learning goals of the domain *Mens & Natuur,* as defined by SLO.[9] The score ranges from 1 to 10, where 1 corresponds to 'the course does not cover the learning goal at all' to a 10 that corresponds to 'the course fully covers the learning goal'.

In one case, I could not be present at the testing and the teacher therefore sent me a short evaluation report.

The survey for the students contained a few questions; one regarding their overall appreciation of the course, and several other questions mainly about how well the 21st century skills are worked with. The results of the surveys are somewhat secondary to the other results; simply because of the limited time I had for the evaluation with students and the limited time I have to both quantitative and qualitative research.

The formats of the evaluation interview and student survey can be found in Appendix B and Appendix C, respectively.

Suggestion: Redesign and re-evaluation (reiterative process)

As resources (mainly time) do not allow for it, a reiteration of this process is not included in this study. However, it is encouraged to conduct further research following this study. Based on the evaluations of the first try-out, changes could be made to create a redesigned course. This course can again be tested, and then evaluated. This is common for design processes as it strengthens the design.

Triangulation

This study draws results by using three different research methods: The literature research, the needs analysis and the design of teaching materials and the evaluation thereof. The aim is to overcome intrinsic biases and strengthen the empirical findings by combining and comparing these three methods. This is a common practice in social science and is called triangulation. Triangulation can be recognized in this study by the reference and linkage of similar results from other research methods.

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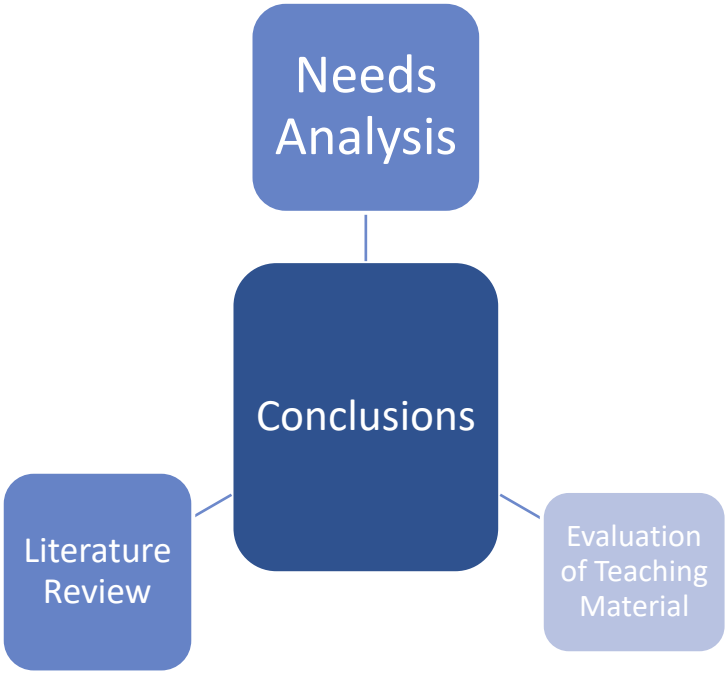


Figure 2: Triangulation of results from needs analysis, literature review and evaluation of teaching material.

Ethics

This study was conducted following the ethical guidelines for educational research by the British Educational Research Association.[10] The participants' privacy was respected and protected. Throughout the report the participants will be referred to as teacher 1/2/3/4 or expert 5/6/7. Their full consent to participation in this study was given and they were informed about the right to withdraw from the study at the start. Un-anonymized data has been removed after completion of this study.

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Results: Needs analysis

The needs analysis was done to identify the gaps that teachers and educational developers experience and where biomimicry may help to close this gap. It specifies the performance discrepancy, between the ideal situation and the current situation. What do teachers miss in the current situation? Where needs to be more focus on? This discrepancy can exist at several layers and aspects of how education is practised. Teachers follow a long road of policies, visions, demands and goals before they decide how to design their classes. They may want to implement subjects differently than prescribed by these guidelines. We therefore need to differentiate between needs that are within the control of teachers and needs that are out of their control. Biomimicry as a design method and BiomimicryNL have therefore little to no control to *directly* fulfil these needs. However, there are ways that BiomimicryNL can *indirectly* help to solve these needs, so they are definitely worth mentioning. This format of needs, with those that biomimicry can have an influence on and those that biomimicry cannot directly influence, was chosen to differentiate the needs that BiomimicryNL can work on from those that are out of BiomimicryNL's reach. It creates an overview of the most crucial and relevant needs. This section provides the findings and results and supports the advice that is given in the conclusions and advice section.

Needs with little to no influence from biomimicry

No influence	Room for extracurricular material
	Attitude of teachers
	Resources

The first category can also be seen as the context for teachers to work in. While these are definitely necessities for teachers, they can influenced most by top-down policies. This is why for this category, the use of biomimicry has little impact. For those needs on which biomimicry could have little to no influence, the most essential need for teachers is the room for extracurricular material. Teachers need to follow learning goals identified by SLO, whilst also taking into account the vision and policies of their school, so the classes are mostly filled with subjects that are decided upon in advance of the academic year. These classes are mostly taught using standard textbooks, like *Biologie Voor Jou* and *Nectar* for biology or *Getal en Ruimte* for mathematics. This discourages teachers to innovate their classes; if the book completely covers the subjects you need to cover, why would you put in effort and do it differently?

The interviewed teachers all indicated that they would prefer more room to innovate their classes. Nevertheless, there is some room for them to innovate, or so they say. The extent to which this is possible depends heavily on the school year. In the *bovenbouw,* the second phase of high school and class 4, 4+5, or 4-6 depending on the level, there is very little room for teachers to take a detour and teach

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extracurricular topics This is because students in de *bovenbouw* prepare for their final exams, which are centrally organized in the Netherlands. However, teachers in the *onderbouw*, teaching the first three years of high school (average age 12-15), have much more room when it comes to this. Here lies an opportunity for BiomimicryNL: focus on the *onderbouw* since there is the most room to inspire teachers. An assumption would be that teachers in the *onderbouw* more readily attend workshops and conventions about biomimicry since they have the most room for extracurricular materials. This is something for BiomimicryNL to keep in mind when organizing workshops or promoting their materials at conventions. Moreover, a solution proposed by one teacher is to make biomimicry material that is interchangeable with standard text books, by focusing on learning goals that cover the to be replaced standard material. This might seem like a common approach but it is important to realize this must also be done when introducing the educational setting to biomimicry. Which exact learning goals could be covered by material about biomimicry was further tested, the results are in the chapter 'evaluations'.

> "Zodra je iets nieuws doet in het onderwijs kom je je collega's tegen die zeggen dat je al zoveel moet. Ik weet niet of zij er bij gebaat zijn als je iets anders gaat doen." – teacher 2
>
> [As soon as you try to do something new in education you have to face colleagues that tell you there is already too much to do. I do not know if they would appreciate you doing something different.] – teacher 2

Secondly, teachers indicate the unwillingness of some of their colleagues to change their approach, method, or to innovate their classes in any way. In most schools that have more than one teacher per subject, teachers design their classes together and decide collectively how to do this. Because designing a class together requires a lot of teamwork, it is easier to follow the rules and go for the standard 'text-book approach' than to come up with new ideas. Especially in the situations where teachers work together, the more 'conservative' teachers adhere to the rules and books and altogether it can be quite difficult to come up with innovative classes. These teachers most often tell others there is too little time to innovate, either for their own preparation or for their class within the schedule of the curriculum. One way to inspire and persuade the more 'conservative' teachers, is by reaching out as many teachers as possible. As soon as one colleague at school is inspired and starts teaching new matters, the other teachers will hear it and might also get inspired, according to teacher 2.

Lastly, the need for teachers which is often more of a restriction, is resources. Next to time, this is mostly materials, and therefore money, and space. It is therefore important for a course to require as few materials as possible and to work with the resources available.

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Needs with influence only by course development

Influence only by course development	Motivation of students - Curiosity - Relevance
	Active learning
	Practicality teachers
	21st century skills - Efficient teamwork - Critical thinking

Then there are needs that biomimicry can fulfil, but the extent to which this discrepancy can be closed is more influenced by teachers or by how the courses are shaped and designed, than that it is influenced by the theory and practice of biomimicry directly. For these needs, teachers themselves have the most impact, although the use of biomimicry can aid them. Using biomimicry therefore does not inherently fulfil these needs; they could possibly also be fulfilled by designing a course that has no biomimicry in it. However, this does not mean that these needs should not be covered. These are actually needs where BiomimicryNL could take much advantage of and it is important that these needs are taken into account when designing biomimicry courses.

First and foremost; teachers need to find the motivation of students for them to better understand the matter and learn progressively better. Student motivation is mostly personal and can have several aspects. Teacher 4 mentions that when teaching with text books, students often find no link to their personal life. She indicates the need for material that can better appeal to the curiosity of the students. The importance of this is also evident from the literature.[21,23] Students need connections to their personal life in order for them to find certain topics interesting or to be willing to find the answers to. She finds that this is especially true when students need to solve problems. Biomimicry as a design method has a strong connection to problem solving, as the design process is often centred around a problem that nature could have answers to. However, it also very much depends on the teacher to find the motivation of students. Teacher 1 has a similar story, but connects this need more to the relevance for students, although this boils down to the same concept of motivation. Overall, working with a nature-based view and thinking of solutions to sustainability challenges give people inspiration and motivation that could lead to better performances. Biomimicry therefore probably leads to higher motivation of students and teachers.

Students also need to consciously experience the learning process, according to several teachers. Teachers need to find ways to involve students more directly in the learning process than they do by teaching from standard text books. This notion corresponds to the active learning teaching method. Biomimicry material could

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incorporate active learning exercises like class discussions, think-pair-shares, learning cells, and student debates. This method and its tools are explained further in the background section.

During the interviews I asked which of the 21st century skills they felt missed in their classes. All teachers indicated they missed creativity and problem solving a lot and critical thinking and analytical thinking to a certain extent. One teacher pointed out teamwork is regularly worked on in class, but could be done better and especially how to work in teams *efficiently* could be improved. These missed skills can be linked to the lack of autonomy and group development in teachers because they need to follow the programme determined by the learning goals in the 'onderbouw' and the exam requirements in the 'bovenbouw'.

> "Nu worden groepjes gemaakt op een willekeurige manier, of met achternamen A-Z. Ik wil studenten in laten zien dat persoonlijke kwaliteiten elkaar kunnen complimenteren en op die manier groepjes indelen. Ook zou ik studenten graag beter willen later evalueren en reflecteren in groepsverband." – Teacher 1
>
> [At the moment students are assigned to groups randomly, or by use of surname, from A-Z. I want students to realize that personal qualities can complement each other, and I want to make groups according to those qualities. Additionally, I would like students to better evaluate and reflect in groups.] – Teacher 1

Biomimicry courses could take up this need and include exercises that let students group themselves by personal qualities and competences.

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Needs with solutions directly inherent to biomimicry method

Influence inherent to biomimicry	Interdisciplinarity - Overlap between subjects - Open problems and questions - Project-based learning - System Thinking
	Student-centred pedagogy - Coaching - Formative assessment - Project-based learning
	Societal Themes - Sustainability - Citizenship
	21st century skills - Creativity - Problem solving - Analytical thinking

The most interesting for this report are the needs indicated by interviewees for which biomimicry as a design method could directly provide a solution for. This could mean that it is so inherent to the biomimicry method, that including this method in courses would automatically fulfil the need and close the discrepancy. Solutions to these needs should therefore also be considered as the true value of biomimicry as a design method: it naturally incorporates these aspects which teachers desperately need in their classes. BiomimicryNL could use this list to promote these values more.

Teachers have been struggling often to create interdisciplinarity at high schools. The secondary school system is so much segregated such that teachers do not dare to cross the border from their own subjects. As teacher 3 notes:

> "Dat is één van de dingen waar we op school echt mee zitten. Elke leraar doet zijn eigen vak, we proberen het wel [om interdisciplinair te werken] maar op de een of andere manier lukt het nauwelijks, óf omdat we niet genoeg overeen kunnen komen of omdat het management in de weg zit." – teacher 4
>
> [it is one of the things we at school really struggle with. Each teacher has its own subject, we do try but somehow it rarely works, either because we cannot find enough common ground or school management is in the way]. – teacher 4

By starting with a problem, consulting nature on solutions, and working out designs, biomimicry naturally stimulates a strong interdisciplinary approach. There is interdisciplinarity on several levels: 'nature' is not only restricted to biology, but connects to all STEM-subjects.. Because solutions to the problems are open to all of nature, students could look at the same problem with different disciplines. For example, the design of a biomimetic train requires expertise from several disciplines: biology, mathematics, physics, engineering, etc. The interdisciplinary aspect of biomimicry allows designing materials around one topic or theme. This opens a gateway to project-based learning. Through active exploration of real-world

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challenges and problems, students acquire deeper knowledge. The subjects that educators teach do not matter; problems are analysed from different fields. Problem-based learning is a style of active learning and thus links to another need indicated by the interviewees.

Whether they are project-based or not; biomimicry courses need to enable students to learn about current societal themes. The themes that teachers missed most in current education were sustainability and citizenship. Sustainability requires little explanation; the theory of biomimicry is deeply intertwined with solving sustainability problems. Whether it is to reduce plastic produce, fight global warming, or bring deforestation to a halt, the biomimicry method pushes students to find solutions that are not only sustainable, but most often regenerative to the earth's ecosystem. This is inherent to the theory since solutions are always found by consulting nature, and nature is always sustainable.

*Burgerschap (*loosely translated as citizenship) as a skill is interpreted by social and cross-cultural interaction and the consciousness of one's own place and responsibilities in the world. If the biomimicry course goes a little bit deeper than only biomimicry on a product level (biomimetics) but also explains the underlying principles and the three elements of biomimicry, ethos, (re)connect, and emulate, then *burgerschap* as a skill is covered really well. Ethos and (re)connect explain the position of humans in the world, and how we should take responsibility.

> "dan zit je toch vaak weer […] aan projecten te denken waar ze in een groepje een bepaalde vraag krijgen […]. Dan coach je ze wel maar moeten ze zelf nadenken hoe ze aan hun informatie moeten komen, luisteren naar elkaar. Ik denk dus dat je ze vrijheid moet geven, het idee geven dat ze zelf eigenaar zijn van hun project. Je moet ze af en toe vast laten lopen, en dan weer verder." – Teacher 3
>
> [Then you should think […] of projects where they have to work in a group and get a certain question […]. You mentor them but they have to consider how to get information themselves, they listen to each other. I think you have to give them freedom, the idea that they are owners of their own project. You have to let them struggle every now and then, and then continue again.] – Teacher 3

Class material should enable students to give them ownership of their own projects, according to the teachers. Teachers would no longer function as teachers but instead mentor students, accompanying them in their learning process, and supporting them where needed. This is a principle that fits in student-centred pedagogy. The focus of instruction here is shifted from the teacher to the student. This allows the student to acquire more autonomy and independence by putting responsibility in the hands of the students. Student-centred learning encompasses many principles discussed as a need in this assessment, so it is a great advantage that the biomimicry method uses this approach.

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Lastly, teachers see a great need for material that enables students to work on creativity, problem solving, and analytical thinking. The skills that teachers miss the most largely overlap with the skills that are least covered by the learning goals, according to a study of Thijs, Visser, and Van der Hoeven.[11] Creativity is barely required, as standard text books have teacher-centred instructions or simple question-answer structures. Biomimicry courses need to sparkle students' creativity more. Problem solving is well-covered by biomimicry when looked at from the challenge-to-biology perspective. Analytical thinking means performing an analysis and doing research. This requires step-to-step instructions and having the students ask questions and look up information. This is incorporated in the theory of biomimicry, but could be brought out more by including actual research steps and explicitly using asknature.org or literature as a source.

Table 3 gives a conclusive overview of all needs that are identified by the needs analysis.

Table 3: an overview of all needs experienced by teachers and educational material developers

No influence	Room for extracurricular material
	Attitude of teachers
	Resources
Influence only by course development	Practicality teachers
	Motivation of students - Curiosity - Relevance
	Active Learning
	21st century skills - Efficient teamwork - Critical thinking
Influence inherent to biomimicry	Interdisciplinarity - Overlap between subjects - Open problems and questions - Project-based learning
	Student-centred pedagogy - Coaching - Formative assessment - Project-based learning
	Societal Themes - Sustainability - Citizenship & System thinking
	21st century skills - Creativity - Problem solving - Analytical thinking

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Results: Literature Research

The literature research resulting in this section was done continuously throughout the study. After conducting the needs analysis, new insights were found and those needed to be researched further by consulting the literature. This section is therefore rather an overview of all background theories needed for this study. It provides a context for all the terms that were stipulated during the needs analysis, which is also why this section follows the needs analysis in this report. The focus points for this literature research are defined by the needs analysis; those are the features in which biomimicry can have the most effect to fulfil the identified need.

STEM

STEM, short for Science, Technology, Engineering and Mathematics, is used to describe a multi-disciplinary strategic curriculum for secondary education that addresses the need to prepare students for scientific careers.[12] The US National Assessment Governing Boards have recognized that students need to acquire skills and abilities associated with designing . These skills are mainly problem solving, evidence gathering and using information. Studying subjects of STEM could help students acquire these soft skills better. Since the focus of this study is on Dutch secondary education, a proper translation of STEM is needed. The term STEM is not commonly known in Dutch secondary education. The current Dutch curriculum has individual subjects that are in relation with each of the STEM-subjects.[13] Since the BioLearn project refers to STEM-education but such a term is not used in Dutch education, the term is 'translated' to all natural sciences for this study. Consequently, learning goals and implementation of the curriculum is described and defined per subject, as explained in the following section.

The Dutch curriculum

The *Nationaal Expertisecentrum Leerplanontwikkeling* (SLO)[13] evaluates and develops the curriculum of Dutch primary, secondary and higher education. Together withschools they test materials and lesson plans and aim to improve the knowledge and professionalism in the educational field. According to Dutch law, schools have some freedom to design their education themselves. The minimal basis of subject-related knowledge what is required is recorded nationally through learning goals.[14] These goals can be related to one subject, a cluster of subjects, or an interdisciplinary field. The governmentally designed goals are evaluated and maintained by SLO. They also provide schools with guidelines and suggestions for implementation of these learning goals. Schools are not obligated to follow these guidelines but are encouraged to use them to understand how the goals can be made concrete.

The goals are structured per domain. These are the domains:

- *Digitale geletterdheid,* digitalization
- *Engels,* English

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- *Nederlands,* Dutch
- *Rekenen & Wiskunde,* mathematics
- *Burgerschap,* citizenship
- *Bewegen & Sport,* sports
- *Kunst & Cultuur,* arts & culture
- *Mens & Natuur,* human body & nature
- *Mens & Maatschappij,* people & society

As an example, these are the learning goals for the domain 'Mens & Natuur', freely translated from a report of SLO:[14]

- The student learns how to transform questions about natural scientific, technological, and healthcare related subjects into research questions, how to perform a study in the natural scientific field and how to present the outcomes of such a study.
- The student learns how to perceive knowledge in key terms in the living and non-living natural domain and how to connect these terms with situations from daily life.
- The student learns how people, animals and plants are in relation to each other and to their surroundings, and how natural scientific applications can both positively and negatively affect the sustainable quality of those interactions.
- The student learns interactions from non-living and living nature by doing practical work.
- The student learns how to work with theories and models by doing research on natural and chemical phenomena such as electricity, sound, movement, energy and matter.
- The student learns how to acquire knowledge about relevant technical products and systems by doing research, how to extract value from these, and how to design and create technological products in a structured manner.
- The students learns how to understand core principles of the structure and functioning of the human body, how to connect these principles to improve physical and mental health and how to take responsibility in doing so.
- The student learns about health and care for himself, others and his surroundings, and how safety of his own and others can be positively influenced in different living situations.

These learning goals provide an overview of what biomimicry courses need to cover for them to be more attractive to be implemented in the curriculum.

As the project of curriculum.nu is yet to be finished, the learning goals have not been developed yet, nor is there much information about how learning goals could be implemented in the classroom. How teachers design their classes will still contribute majorly to the learning process of students. When Curriculum.nu finalizes its project, schools need to be given the tools to implement the new curriculum into their classrooms. This possibly requires a whole new perspective on how education is

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practiced. While there are several revolutionary educational practices, one possible learning method to be used as a tool for Dutch education is biomimicry.

Educational Innovation

The SLO acknowledges there is a need for innovation in the educational setting. They therefore established Curriculum.nu,[15] an organization that works towards a report meant to advise the Dutch government how to design the future curriculum starting in 2030. According to curriculum.nu, it is important that societal needs are adapted to the classroom. As students grow up, they need to get acquainted with what is demanded from them in the future. They therefore strive, together with SLO, to continuously evaluate and re-innovate the educational outlook.

For their advisory report they use the observations of experts on to what extent their developments fit into recent subject related developments. Additionally, the experts evaluate the manner of overlap within curricular study areas. In addition to the experts, they have an advisory committee consisting of members with backgrounds in curricular developments and educational sciences.

As provisionaldevices for what end-products will be created by this project, curriculum.nu has documented their vision per domain. In the vision document for the domain 'Mens en Natuur'[9] it is explained that the learning goals of this domain revolve around four current societal developments, called the pillars within this domain:

- Technology
- Sustainability
- Science
- Health

A focus in the rest of the document lies on how this domain contributes to the maintaining of life on Earth and its economy. According to their vision, this maintaining is done through technological innovations which are driven by scientific discoveries. Students need to learn about these developments and technological innovations by exploring themselves and the world from a curious and intrigued outlook. Nature needs to be stimulated and fostered. From a student perspective, the world is a playing and learning area, allowing students to experience its complexity and cohesiveness. The vision to allow students to discover the world, learn about technological innovations all in perspective from the 4 societal developments, needs to be coordinated throughout the learning goals to be developed by curriculum.nu.

Interestingly, these four pillars described by curriculum.nu is also what is acknowledged to be the critical themes to be covered by the teachers in the needs analysis. Material about biomimicry should have students acquire deeper knowledge within one of these four themes.

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The curriculum of the 21st Century

As SLO and curriculum.nu formulate, students need to be prepared for problems of the future.[9] Society has undergone an immense transformation over the last decades with the fast-improving technology and economy. Students need to be prepared to adapt to these movements in the 21st century, for which a set of skills are needed for success as proposed by educators, business leaders, academics and governmental agencies. These skills are called the 21st century skills, as first described by Trilling, Bernie and Fadel.[16] These skills differ from academic skills as these skills are not primarily based on acquiring knowledge directly, but more about the process of acquiring this knowledge. They can also be referred to as “soft skills” or “applied skills”.

Trilling, Bernie and Fadel first modelled these skills and grouped them into three main areas:

- Learning and innovation skills:
    - Creativity
    - Innovation
    - Communication & Collaboration
    - Problem Solving
    - Critical Thinking
- Digital literacy skills:
    - Information literacy
    - Media literacy
    - Information and communication technologies (ICT)
- Career and life skills:
    - Flexibility and adaptability
    - Self-regulation
    - Social and cultural interaction
    - Productivity

After their model, several studies and models followed.[17] The 21st century skills defined vary per model but share these common themes. These models all share that there is a specific pedagogy needed that involves creating and analysing, working together with others, presenting and sharing learning experiences and evaluating the process. This is in contrast with traditional learning which involves regurgitation of knowledge to teachers.

Two well-known models are the P21 and the Four Cs models,[18] which are explained in the figures below.

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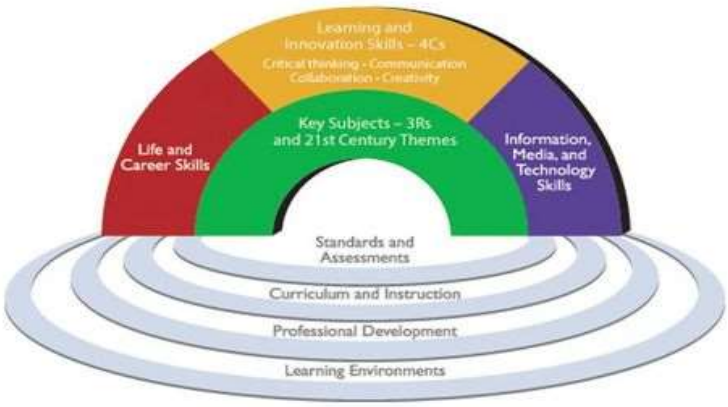


Figure 3: The P21 Model describing how 21st century skills are organized.

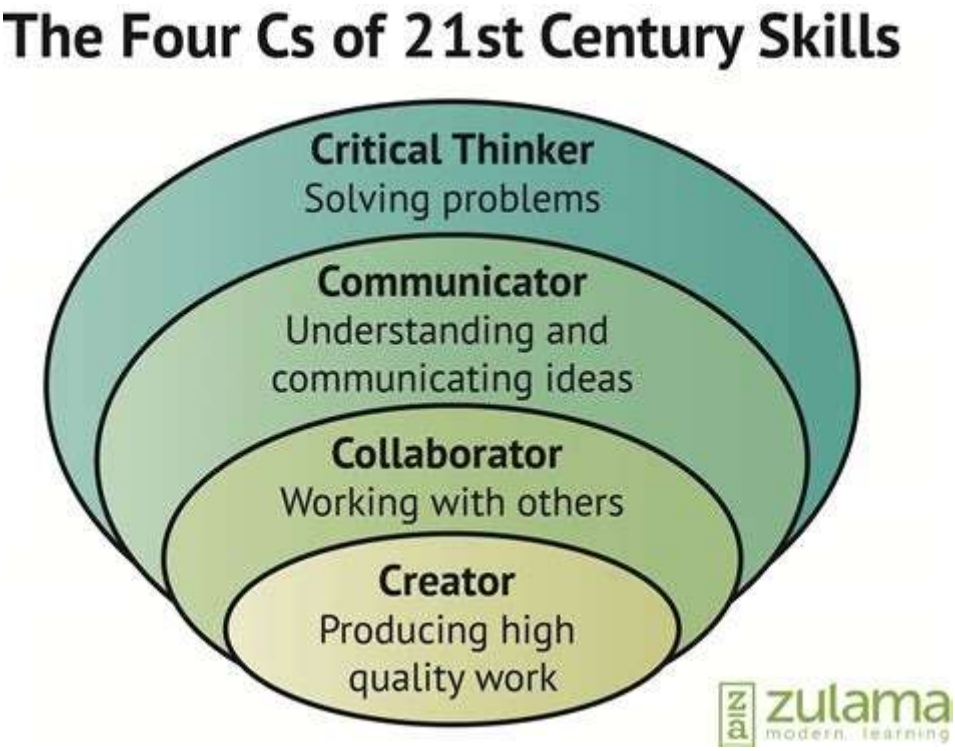


Figure 4: The Four Cs model describing how 21st century skills are organized.

The study by Thijs, Fisser and van der Hoeven[11] aimed to define how 21st century skills are integrated in the learning goals set by the Dutch government through SLO. For this, they used a collection of several models describing the skills and looked for overlap between the models and the learning goals. The analysis consisted of two parts, the first one being on the direct appearance of 21st century skills in the learning goals itself, the second one being on the appearance within the plans for

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specifications and implementation of the learning goals. The skills that are mentioned in the learning goals the most times are:

- Communicating
- Self-regulation
- Social and cultural skills

There is little attention in the learning goals for:

- Problem solving
- Teamwork
- Digital literacy
- Creativity

For the specification and implementation of the learning goals, the following observations were made:

1. The specific attention for the soft skills are scattered across the different domain plans.
2. Not all sub-skills of the 21st century skill models are mentioned in the specifications, which means that the 21st century skills are not fully covered in many cases.
3. Similar to the learning goals themselves, the specifications give little attention to the following skills:
    a. Creativity
    b. Problem solving
    c. Teamwork

The researchers advise that, in order to be compliant with the 21st century skills, the curriculum needs to reflect an integrated approach in which skills are linked to specific subject related knowledge. In addition, schools need to be given the space to allow for school-wide application and implementation of the learning goals. This initiates ownership and innovativeness within and between schools.

The findings of the needs analysis are in line with this study as the teachers indicate that the 21st century skills that are missing most in the current curriculum are creativity and problem solving. They also support the idea that biomimicry inherently has great potential to incite students to work on these soft skills. Especially creativity is most needed and best covered by biomimicry, according to the teachers and experts.

Onderzoekend & Ontwerpend Leren

The principles of biomimicry are said to closely correlate to those of *Onderzoekend (*learning by doing research) *& Ontwerpend Leren (*learning by designing).[19] This is a teaching method that stimulates students to actively investigate and discover the world around them. The curiosity that children naturally have plays a key role in this method. Two cyclic processes are followed in this method; one for *onderzoekend leren,* the other for *ontwerpend leren*.[20]

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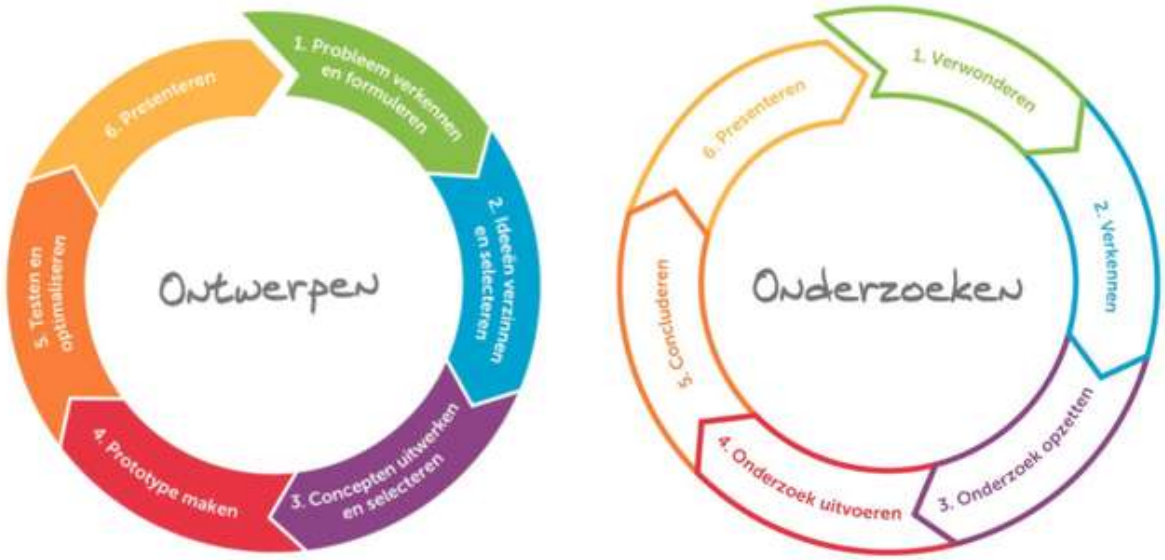


Figure 5: The cycles of 'Ontwerpen & Onderzoeken'

The cycle of the learning by research starts with a confrontation of a new problem, phenomenon or object that connects to the (social) environment of the students. After exploring the problem and investigating it from the broadest possible view, students design their research setup. They carry out this plan and base their conclusions on their findings. These are presented. The other cycle describes learning by designing, which is similar to the other cycle. However, instead of planning their research, students make a design proposal which is tested and evaluated before presenting.

Student-based pedagogy

Over the years, the focus of teaching is shifting more and more from the teacher to the student. This is what the teachers indicate, but they argue this is also what needs to be more focus on. Student-centred learning[21] is an umbrella-term for a collection of methods that aim to develop autonomy and independence of students by imparting them with skills on how to learn a subject and letting them own the responsibility of their own learning path.

The way of assessment is one of the most critical difference between teacher-centred learning and student-centred learning. The latter typically involves more formative assessment,[22] which uses qualitative feedback for both student and teacher focusing on performance. This opposes summative assessment which is associated with scores and quantitative ways to monitor outcomes.

The role of the teacher changes when following student-centred learning, as they now do not deliver the information to the students, but the students do so themselves.

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They act more like a coach, one that guides students in their learning process, by asking questions and giving advice.

One of the methods that laid the groundwork of student-based pedagogy is project-based learning (PBL).[23] This comprehensive approach is designed to connect to the inner motivation of students and have them understand the subject for their own interest instead of for passing a test. The dynamic classroom approach involves students learning about a subject by working to investigate and answer a complex question or problem.

Interdisciplinarity

Project-based learning has proven to be successful.[24] A possible factor contributing to this success is the limitless interdisciplinarity that could be incorporated. Interdisciplinarity is best defined as when distinctive components come from two or more different disciplines.[25] In the study of Nissani,[25] it is argued that the biggest obstacle of the implementation of interdisciplinarity is that most participants in interdisciplinary ventures are educated in traditional single disciplines. They have not learned to think in other ways than that their discipline prescribes. Because interdisciplinary thinking is said to increase one's ability of critical thinking, communication, creativity, and pedagogy,[26] it is critical to educate students with interdisciplinary approaches early on. Biomimicry is said in the needs analysis to contribute to an interdisciplinary approach, as it provides open questions with multiple views and aspects to be investigated without those being predefined beforehand.

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Results: Testing & Evaluation

The developed courses were tested 4 times in total. I was present at three out of four of the testing to evaluate the course together with the teacher. I made a number of observations during the testing of the two biomimicry courses that are worth mentioning. During the first test I noticed that the introduction about biomimicry lacked information in the course guide. Students (and some teachers) are often new to the concept of biomimicry, so for them to work with biomimicry requires a thorough introduction. This should include many examples on the product, process and system level. Especially the last two are important, such that students get the notion that biomimicry is more than copying nature for product designs. The notions of sustainability, regenerative cultures and circular economy should be explained as well. This allows the student to understand the context of biomimicry better.

Secondly, students struggled most in key phases of the biomimicry process: identifying functions and translating those functions to nature. Identifying functions is difficult, especially when it is the first time students work with biomimicry. It is here that the teachers could use more help guiding students the right way. Perhaps some questions could be phrased in the course that teachers can ask students to guide them. This also brings out the role of teachers as mentors, guiding them instead of lecturing them.

Evaluations teachers: General

As explained in the methods section, teachers evaluated the courses and provided interesting insights and ways to improve the courses. The point that was mentioned maybe the most, for both courses, was that the teachers' guide needs to be much more extensive. Teachers that are not familiar with the concept of biomimicry have an extra challenge on how to guide students in the learning process. The teacher's guide should therefore incorporate a time schedule, the learning goals covered and small explanation how to properly execute each assignment. In order to help guide students better, questions that teachers could ask students could be phrased in the guide. Teachers should get a small overview of what biomimicry entails, and how they should guide students in the biomimicry design process.

The learning goals that are covered should be investigated. In the needs analysis, many teachers indicated that they need material that works with learning goals, such that they could work the material into the standard curriculum. Therefore, the biomimicry courses should investigate which learning goals are covered, and material from standard text books could be replaced because its learning goals are covered by the biomimicry course.

Another suggested improvement is to create courses that are also available online. Many schools have students work with tablets or laptops, so the created courses should follow that development. When courses are available online, there are many

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opportunities to include more interactive material, such as videos, assignments, online questionnaires and quizzes.

Evaluations: Marvellous Models

The course 'Marvellous Models' provides a very good introduction to biomimicry, according to both teachers that tested this course. They explained that the course stimulates students to look at nature more carefully and start seeing the value of the world around them. The format of the course follows the process of research very well, which allows students to think critically and design their own research.

However, both teachers indicated that the course is still steered towards nature a lot, and does not allow students to look at problems from different perspectives or disciplines. Since students have to go outside to look for organisms that they can deduct natural models from, they are limited by the organisms they find outside. The course should include more assignments that actively encourage students to investigate more aspects, such as the mathematical, physical, or chemical processes behind the models from nature.

One teacher also evaluated how well this biomimicry course connects to the learning goals as defined by SLO (see background section). The goals that were covered to any extent are shown in table 4. The rest of the learning goals were all scored with a 1/10.

Table 4: Scoring of how well the course 'Marvellous Models' matches with the learning goals of the domain Mens & Natuur.

Learning Goal	**Score (1 = does not cover at all, 10 = fully covers)**
The student gains insight in processes from non-living and living nature and how they interact with their environment by doing practical work.	5
The student learns how to transform questions about natural scientific, technological, and healthcare related subjects into research questions, how to perform a study in the natural scientific field and how to present the outcomes of such a study.	4
The student learns how to perceive knowledge in key terms in the living and non-living natural domain and how to connect these terms with situations	4

A minor point of evaluation which the teacher that conducted the test of this course without my presence indicated was that there was not enough time to complete the course by the end of the two classes of 50 minutes. The other test class did succeed to finish the course in time, although the total duration of their classes was 135 minutes

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instead of the 100 minutes scheduled usually (for Dutch secondary schools) for two classes.

Evaluations: Packaging

According to the teachers, the course 'Packaging' was very useful to use for students to get an introduction to designing. The course uses a method that is in line with that of *onderzoekend & ontwerpend leren*. Since they have to make their own design, there are many different answers possible and students can investigate the subject from different aspects and angles. The course can be used for different subjects, as one teachers used it in a *NaSk* class while the other used it in a *Science* class. However, to guide teachers better and stimulate them to choose this course for different subjects, the course could include more examples and aspects from different fields of study.

It should be made clear that, in this course, teachers should take the role of coaches more than that of instructors. They are not required to know all the answers to the questions that students have, but should guide the students in investigating the problems themselves.

Both teachers evaluated how well this course covers the learning goals. The learning goals that were covered to any extent are given by table 5. All other learning goals scored a 1/10.

Table 4: Scoring of how well the course 'Packaging' matches with the learning goals of the domain Mens & Natuur.

Learning Goal	**Average Score (1 = does not cover at all, 10 = fully covers)**
The student learns how people, animals and plants are in relation to each other and to their surroundings, and how natural scientific applications can both positively and negatively affect the sustainable quality of those interactions.	7.5
The student learns how to transform questions about natural scientific, technological, and healthcare related subjects into research questions, how to perform a study in the natural scientific field and how to present the outcomes of such a study.	4
The student learns how to perceive knowledge in key terms in the living and non-living natural domain and how to connect these terms with situations from daily life.	3.5
The student gains insight in processes from non-living and living nature and how they interact with their environment by doing practical work.	2.5

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The student learns how to acquire knowledge about relevant technical products and systems by doing research, how to extract value from these, and how to design and create technological products in a structured manner.	2

One minor point of evaluation for this course was that the tables of the assignments were too small, more space per row and more rows should be added. Moreover, a suggestion by one of the teachers was to offer this course online in a shared space like Google Drive, such that teachers could still edit the student material and add their personal improvements to the course.

Student evaluation

Table 5 shows the most important results of the student evaluation survey. For the surveys with all questions that were asked, see Appendix C.

Table 5: The most important results of the student evaluation surveys of the courses 'Marvellous Models' and 'Packaging'.

Evaluation	**Score 'Marvellous Models' (n = 27)**	**Score 'Packaging' (n = 35)**
Average overall appreciation score (1-10)	6.7	7.8
Which aspect do you think is most important to learn in this course (most answered)	That I learn to think about applications of functions in nature	That I learn to think about applications of functions in nature
Do you think it is more effective to do the assignments of this course in groups or alone? (most answered)	In groups	In groups
How much did you learn about the organism you studied? (from 1-4, where 1 is nothing and 4 is a lot)	3.1	2.9

The overall appreciation score varied somewhat across the classes where the courses were tested. Especially for the course 'Marvellous Models' the score different between the two classes: 7.6 in one class (n = 9) and 6.1 in the other (n = 18). The standard deviation for the scores in the second class with 18 students was also quite high, 1.9. This indicates that there is a wide range in appreciation of this course among that class.

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Discussion

The group that is able to make great changes in education is that of the teachers.[27,28] They are the one designing their classes, choosing materials, methods and teaching approaches. They are the ones that influence the learning process of the students. As the results of the student evaluation shows, there is quite some difference in the appreciation of the course between the different test schools. This could imply that the teacher has a great impact in how students experience a course, among other implications. Additionally, teachers indicated in the interviews for the needs analysis that one of the factors for the choice of course material is their intrinsic motivation, and that it is sometimes difficult to organize innovative courses if 'conservative teachers' hinder the process. Future research should therefore focus more heavily on the intrinsic motivation of teachers. How do they decide what passes as a class and what does not? This study already had some interesting findings on those questions, so this should be expanded in the next study. The ability to research the intrinsic motivation in this study was also fairly limited by the goal that the BioLearn project has set in this point of time; to develop biomimicry material. The focus lies on developing courses. For next projects it would therefore be interesting to consider how to find the motivation of teachers and how to best reach out to teachers. The BioLearn project will focus on that more in the coming year.

The fact that this research was done with the aim to provide more information for the BioLearn project, which gives this report an additional *advisory* function, also has some limitations to the validity of this study. Because the research is done with BiomimicryNL's goal in mind; *to use biomimicry to work towards a circular economy*, while the question of this study is whether biomimicry could have a role in secondary education, the results could produce one-sided views that better the position of biomimicry. To prevent limiting the internal validity of the study this way too much, the questions asked in the needs analysis and evaluation interviews were aimed to be as neutral towards biomimicry as possible.

Perhaps one of the most influential decisions taken in this study was to only select teacher participants with knowledge about biomimicry. This decision was primarily based on the fact that resources were limited. Would there have been more time, participants were chosen that do not have knowledge about biomimicry, to see what their first impressions were after telling them about the concept. This argument coincides with the notion many teachers gave in the interviews. They indicated that they struggled with 'conservative' teachers that do not find the need to innovate their classes too much. It would have been extremely interesting to let these teachers participate in this study, because they are the teachers in the Netherlands that are needed to make a change in the educational setting. They are the hardest to convince. The teachers that were interviewed were most probably already very enthusiastic about biomimicry and therefore generate a bias for the needs analysis. Future research should focus on finding the 'conservative ' teachers and analyse why they would not be willing to take up biomimicry.

In this line of thought, most teachers that participated in this study taught *HAVO* or *VWO*, the higher levels of high school. It therefore covers less than half of all

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students, since most students go to *VMBO*.[13] A big opportunity lies to investigate *VMBO* classes, and to see whether the findings overlap with this study. There were simply no *VMBO* teachers that responded to the repeated requests to participate reached out so this could not be studied. An assumption would be that *VMBO* teachers have less room to innovate their classes and are more stuck to regular text books and the learning goals. One definite reason which probably influenced this is that the participant selection was done rather late in the academic year; most teachers indicated they were either too busy, or that they did not have room in their schedule to test out the courses. Since *VMBO* only has 1 year in the *bovenbouw*, those students in the last year were busy preparing for final exams in the time of participant selection, while *HAVO* and *VWO* also have years in the *bovenbouw* during which students take no final exams yet.

A note to be taken should be that the process of design knows many reiterations and evaluations. To improve the designed courses of this study even more, they should be re-evaluated, redesigned and tested again. This cycle of designing, testing, and evaluating continuous as the curriculum changes.

The further evaluation and testing of biomimicry courses should be complemented with a more thorough assessment of the learning goals and the role of biomimicry in these goals. One of the findings in the needs analysis was that teachers in their choice of courses and methods often look to what extent a course covers certain learning goals. To serve the needs of the curriculum better, and therefore those of students and teachers, an extensive learning goal assessment could provide crucial information on where biomimicry could fit in the identified gaps. The results of the teacher evaluations of the learning goals indicate that only some learning goals are covered in the courses, and only to some extent. There is major room for improvement for Biomimicry and BiomimicryNL on this aspect.

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Conclusions & Advice

Biomimicry as a design method has great potential for secondary education. With the changes coming up for the curriculum of Dutch secondary education,[9] many opportunities lie for biomimicry to be implemented. Educational developers of curriculum.nu and SLO are working on new learning goals that should be implemented in the coming years. These goals should close the gap of what society expects from students and what students are taught in school. This gap has become clear by the results of the need assessment, see Table 6. The table gives an overview of the criteria that developers at BiomimicryNL or outside should adhere to when developing biomimicry courses.

Table 6: A list of criteria for a biomimicry course.

Criteria Biomimicry Course

Class material about biomimicry needs to:

- Appeal to students motivation: sparkle their curiosity and relevance by including examples from day to day situations, have students think about relevance
- Allow active learning by having students consciously experience the learning process. Educational tool suggestions:
  - Class discussions
  - Think-pair-shares
  - Learning cells
  - Student debates
- Make it as easy and practical for teachers as possible, by
  - Lowering resources needed: time, materials (money), space
  - Having an extensive teacher's guide
- Take a student-centred approach by enabling
  - Coaching instead of teaching
  - Formative assessment
  - Project-based learning
- Give room for interdisciplinarity
  - Find overlap between STEM-subjects and use them
  - Provide open problems that can be tackled from multiple perspectives
- Incorporate societal themes
  - Sustainability
  - Citizenship & System thinking
- Enable students to develop 21st century skills
  - Creativity
  - Problem solving
  - Analytical thinking
  - Efficient teamwork
  - Critical thinking

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There is a strong correlation between the needs that are indicated in the needs analysis, the needs that curriculum.nu is working on to improve in the coming redesign of the educational setting and the strongest features of biomimicry. The important suggestion is to adhere to new ways of teaching as much as possible. Teachers indicate they want materials that enable student-centred learning, which sparkles students' curiosity, allow active learning, and integrate this in interdisciplinary project-based material that fully cover the most needed 21st century skills. The literature research suggests that these features could indeed possibly define the new educational setting, confirming the findings of the needs analysis.[16,21,24] These features are exactly where the intrinsic value of biomimicry lies, according to the results of the needs analysis. The need for more implementation of *onderzoekend & ontwerpend leren* and the correlations in the principles between biomimicry and *onderzoekend & ontwerpend leren* suggest that biomimicry could provide a fitting educational setting where *onderzoekend & ontwerpend leren* is practiced.

The biomimicry courses that are developed in the first phase already cover these correlated needs to an extent, but the evaluations (see Tables 7 and 8 for conclusions) indicate much more can be improved for next versions to be developed.

Table 7: Evaluations of both biomimicry courses

Evaluations	
Marvellous Models	**Packaging**
+++	+++
Very good introductory course to biomimicry. Critical and analytical thinking is covered well.	Problem solving and creativity are well covered. The course provides a typical biomimicry process, which allows to enable the values of biomimicry to be covered. Interdisciplinary approaches are also possible in this course
---	---
Does not incorporate interdisciplinarity. Might	Barely allows the students to think from different perspectives, or steer them towards looking up different aspects.
Advice for Marvellous models	**Advice for Packaging**
• Include assignments that allow students to investigate problems from different perspectives and expertise. • Include a time management sheet, with indications of duration per assignment, and consider to scrap assignments (or make them optional) due to time constraint (for 2x50 min).	• Include examples and background information from different fields. This course has potential to be used for different subjects (like *NaSk, Biologie, Onderzoeken & Ontwerpen)* but make the course attractive to be used for these courses. • Reformat the student material: enlarge the tables, give more space for students' answers.

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Table 8: General advice for both courses

General Advice for both courses
1. The teachers' guide needs to be much more extensive. Teachers that are not familiar with the concept of biomimicry have an extra challenge on how to guide students in the learning process. The teacher's guide should therefore incorporate a time schedule, the learning goals covered and small explanation how to properly execute each assignment. In order to help guide students better, questions that teachers could ask students could be phrased in the guide. 2. Assign learning goals to courses, and consider which parts of standard curriculum could be replaced by biomimicry courses 3. The courses require a more extensive introduction about the basic principles of biomimicry. Lots of examples need to be included, with as much as interactive material as possible. 4. Develop online versions of the courses, since many classes are taught partly online. This way, more online tools can be used, such as Serious Games and Shakespeak.

An important note is that the teachers are the ones with the most power to make a change: they decide 'how the classroom looks like'.[28] BiomimicryNL should focus on inspiring teachers, and investigating their intrinsic motivation further. Inspiring one teacher could cause a ripple effect and possibly inspire other teachers of the same school or in the network. Offering training in biomimicry might also be a great boost to reach out to more teachers. Especially the more 'conservative' teachers are difficult to reach: the best way to reach them is perhaps to promote biomimicry more and more by giving workshops and trainings. See Table 9 for more advice on the course implementation and reach out to teachers.

Table 9: General advice for the implementation of the courses, gathered from the data of the needs analysis and the course evaluations.

Implementation Advice
• It is fine to use the term biomimicry, but do not adhere to 'biomimicry' term too much; offer material with the value of 21st century skills and different approaches as the selling point. Do not use it for titles and in descriptions used for promotion. To still include the theory of biomimicry and nature's principles, it is better to introduce the term later in the course. - Use 'learning from nature' or 'inspired by nature' or 'bio inspired' • Focus on the values of biomimicry courses (see needs analysis), promote these and the added value of biomimicry better • Reach out to teachers via workshops and conventions • Ask to write a piece in educational biology papers like Bionieuws, the newspaper of NIBI • Offer developed courses on course databases - biologiepagina.nl - wikiwijs.nl

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A final conclusion from this study is that biomimicry as a design method provides crucial links to these needs. These links could provide the base of how biomimicry should be implemented in secondary education, and how BiomimicryNL can influence the transition to a circular economy by tackling problems and opportunities by the roots: education.

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Appendices

Appendix A: Format Interview Needs Analysis

Introductie

- Doel Onderzoek
- BiomimicryNL
- Vertrouwelijkheid
    - (Volledige anonimiteit)
    - Transcript toesturen
- Uitleg format interview

*** BEGIN OPNAME ***

1. **Wat is je achtergrond (relevant voor dit onderzoek)?**

LERAAR Hoe ziet de gemiddelde klas er nu uit?

2. **Hoeveel ruimte heb je om je eigen invulling te geven aan de les? Hoe doe je dat?**

3. **Tegen welke moeilijkheden loop je aan bij het inrichten van jouw lessen of het kiezen van methodes?**

4. **Welke lesmethodes gebruik je?**
    - **Welke aanpak?**

5. **Welke (maatschappelijke) thema's komen aan bod? Welke missen er?**

EXPERT Hoe ziet een gemiddelde cursus die jullie geven er nu uit?

6. **Hoe ziet een gemiddelde les die jullie geven eruit?**
    - Didactiek
    - Lesstof
    - Soft Skills

7. **Is er veel vraag naar lessen rondom de verplichte stof of juist daarbuiten?**

8. **Is er veel ruimte voor scholen en docenten om dit soort activiteiten in te plannen?**

9. **Hoe komen jullie in contact met scholen? Gaan jullie zelf op zoek of worden jullie benaderd?**

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10. **Om leerlingen beter voor te bereiden op hun toekomst, zou er buiten de verplichte lesstof andere lessen en activiteiten nodig zijn?**

Achtergrond: Biomimicry

Biomimicry draait dus om het nastreven van de genialiteit van de natuur op het gebied van ontwerpen van producten, processen en systemen. Er is sinds 3,8 miljard jaar leven op aarde aanwezig. Dit heeft zich ontwikkeld van de eerste basale levensvormen tot de vaak zeer geavanceerde levensvormen die we nu in de natuur tegenkomen. Sinds het ontstaan van de eerste levensvormen hebben de organismen en (eco) systemen op aarde uitgevonden wat werkt, wat passend is binnen de context en wat bijdraagt aan overleven. De natuur is in staat op de meest economische manier haar doelstellingen te behalen in termen van energie en materiaalgebruik.

Vaak streven de oplossingen ontwikkeld in de natuur onze oplossingen aan alle kanten voorbij. Oplossingen ontwikkeld in de natuur zijn vaak ingenieus, duurzaam en stabiel onder veranderende omstandigheden. Ze hebben mede daardoor een laag risico.

11. **Wat spreekt jou in dit verhaal aan? Welk aspect van biomimicry vind je interessant?**

12. **Op welke thema's die behandeld worden in de klas zou dit goed aansluiten? Hoe zou dit behandeld kunnen worden in de klas? Als lesstof of als leermethode?**

13. **Op welke manier denk je dat biomimicry een meerwaarde in de klas kan hebben?**

14. **Zou een lesmethode over biomimicry interessant zijn voor leerlingen? Waarom? Hoe zou het interessanter gemaakt kunnen worden?**

15. **Welke aspecten van biomimicry spreken aan bij de docent?**
    - **Didactiek**
    - **Inhoud**
    - **Aanpak**

16. **Hoe kan biomimicry beter onder de aandacht van docenten en leerlingen gebracht kunnen worden?**
    - **Implementatie binnen het curriculum**
    - **Sturen op inhoud dat aansluit bij vakinhoud**
    - **Van buitenaf blijven aanbieden (e.g. BiomimicryNL)**

Achtergrond: 21st century skills

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Uitleg: SLO en curriculum.nu werken aan het herinnoveren van het Nederlandse curriculum. De toekomstige eisen voor de leerling spelen een belangrijke rol in het bepalen van de leerdoelen. Ze proberen 21st century skills (= soft skills) in de leerdoelen te verwerken aan de hand van de vakinhoudelijke kennis die opgedaan moet worden.

21st century skills in alle modellen:

- Samenwerking
- Communicatie
- ICT-gebruik
- Sociaal/Cultureel bewustzijn (inc burgerschap)

In de meeste modellen wordt genoemd:

- Creativiteit
- Kritisch denken
- Probleemoplossende vaardigheden
- Productiviteit

17. **Is er aandacht in het huidige onderwijs voor het aanleren van deze competenties?**

18. **Ben je van mening dat de 21st century skills standard aangeleerd moeten worden in het onderwijs? (welke wel en welke niet?)**

19. **Wordt expliciet hieraan gedacht bij het ontwikkelen van lessen? Op welke manier?**

Studie wijst uit:
Alle 21-eeuwse vaardigheden komen aan de orde, maar vaak in geringe mate.
De vaardigheden die het meest aan de orde komen zijn:
- Communiceren
- Zelfregulering
- Sociale en culturele vaardigheden

er is weinig aandacht voor probleemoplosvaardigheden en samenwerken. Ook digitale geletterdheid komt in beperkte mate voor. Er is beperkt aandacht voor creativiteit.

In de wijze waarop de vaardigheden zijn uitgewerkt in de concretiseringen valt een aantal zaken op:

- De aandacht voor de vaardigheden is versnipperd
- Niet alle subvaardigheden die horen bij de acht vaardigheden komen aan de orde in de concretiseringen. De vaardigheden komen daarmee niet altijd in voldoende diepgang aan bod.
- De vaardigheden creativiteit, probleemoplosvaardigheden en samenwerken krijgen (ook) in

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de concretiseringen weinig aandacht.

20. **(Ter bevestiging van vraag 16) Wordt deze observatie door jou gedeeld?**
21. **Hoe zouden in jouw klas / voor jouw lesmethode deze 21st century skills naar voren moeten komen?**
22. **Zou er in lesmethodes over biomimicry veel of weinig aandacht zijn voor soft skills / 21st century skills?**
23. **Vaardigheden beginnen een steeds belangrijkere rol te spelen binnen het onderwijs. Op welke manier zou biomimicry aan deze innovatie kunnen bijdragen?**

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Appendix B: Evaluation Interview Teachers

Vragenlijst Docenten Test Module 'Meesterlijke Modellen'

1. In welke klas is deze course getest?
2. Hoe was de tijdsinschatting? Hoeveel tijd was er nodig?
3. Sluit de opdracht aan op het niveau van de leerlingen?
4. Was de module goed te begrijpen voor de leerlingen?
5. In welke mate sluit de course aan bij de volgende leerdoelen van Mens & Natuur? Geef een cijfer van 1 (sluit helemaal niet goed aan) tot 10 (sluit heel goed aan)
    a. De leerling leert vragen over natuurwetenschappelijke, technologische en zorggerelateerde onderwerpen om te zetten in onderzoeksvragen, een dergelijk onderzoek over een natuurwetenschappelijk onderwerp uit te voeren en de uitkomsten daarvan te presenteren.
    b. De leerling leert kennis te verwerven over en inzicht te verkrijgen in sleutelbegrippen uit het gebied van de levende en niet-levende natuur, en leert deze sleutelbegrippen te verbinden met situaties in het dagelijks leven.
    c. De leerling leert dat mensen, dieren en planten in wisselwerking staan met elkaar en hun omgeving (milieu), en dat technologische en natuurwetenschappelijke toepassingen de duurzame kwaliteit daarvan zowel positief als negatief kunnen beïnvloeden.
    d. De leerling leert onder andere door praktisch werk kennis te verwerven over en inzicht te verkrijgen in processen uit de levende en niet-levende natuur en hun relatie met omgeving en milieu.
    e. De leerling leert te werken met theorieën en modellen door onderzoek te doen naar natuurkundige en scheikundige verschijnselen als elektriciteit, geluid, licht, beweging, energie en materie.
    f. De leerling leert door onderzoek kennis te verwerven over voor hem relevante technische producten en systemen, leert deze kennis naar waarde te schatten en op planmatige wijze een technisch product te ontwerpen en te maken.
    g. De leerling leert hoofdzaken te begrijpen van bouw en functie van het menselijk lichaam, verbanden te leggen met het bevorderen van lichamelijke en psychische gezondheid, en daarin een eigen verantwoordelijkheid te nemen.
    h. De leerling leert over zorg en leert zorgen voor zichzelf, anderen en zijn omgeving, en hoe hij de veiligheid van zichzelf en anderen in verschillende leefsituaties (wonen, leren, werken, uitgaan, verkeer) positief kan beïnvloeden.
6. Was de course praktisch goed uitvoerbaar?
    a. Voorbereiding
    b. Gevraagd niveau docent
    c. Benodigdheden
7. Andere feedback

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Appendix C1: Student Evaluation Survey 'Marvellous Models'

1. Hoe leuk vond je deze les over 'meesterlijke modellen'? Geef een cijfer van 1 (niet leuk) tot 10 (heel leuk)									
1	2	3	4	5	6	7	8	9	10

2. Welk aspect denk jij dat het belangrijkste is om te leren van deze les?				
Dat ik anders naar de natuur heb kunnen kijken O	Dat ik kon samenwerken met klasgenoten O	Dat ik meer kon leren over een organisme O	Dat ik kon nadenken over toepassingen van functies uit de natuur O	Dat ik een poster kon maken en deze presenteren O

3. In het onderdeel 'Op zoek naar functie' moest je functies van natuurlijke modellen omschrijven. Hoe goed lukte dat?			
Helemaal niet goed O	Niet heel goed O	Een beetje goed O	Heel goed O

4. Tijdens het onderdeel 'Vragen leren stellen' moest je vragen stellen over dingen van het organisme dat je bestudeerd hebt. Denk je dat je deze opdracht beter alleen, of met z'n tweeën had kunnen doen?	
Alleen O	Samen met iemand anders O

5. Hoeveel heb je geleerd over het organisme dat jij hebt bestudeerd?			
Heel weinig O	Weinig O	Veel O	Heel veel O

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Appendix C2: Student Evaluation Survey 'Packaging'

1. Hoe leuk vond je deze les over 'verpakkingen'? Geef een cijfer van 1 (niet leuk) tot 10 (heel leuk)									
1	2	3	4	5	6	7	8	9	10

2. Welk aspect denk jij dat het belangrijkste is om te leren van deze les?				
Dat ik anders naar de natuur heb kunnen kijken O	Dat ik kon samenwerken met klasgenoten O	Dat ik meer kon leren over een organisme O	Dat ik kon nadenken over toepassingen van functies uit de natuur O	Dat ik leer de natuur te gebruiken om ontwerpproblemen op te lossen O

3. In het onderdeel 'Kunnen we slimmer verpakken' moest je functies van een bepaalde verpakking omschrijven. Hoe goed lukte dat?			
Helemaal niet goed O	Niet heel goed O	Een beetje goed O	Heel goed O

4. Tijdens het onderdeel 'Biologiseer je vraag!' moest je vragen stellen over hoe de natuur jouw vooraf bepaalde functies zou vervullen. Denk je dat je deze opdracht beter alleen, of met z'n tweeën had kunnen doen?	
Alleen O	Samen met iemand anders O

5. Hoeveel heb je geleerd over de natuurlijke modellen dat jij hebt bestudeerd?			
Heel weinig O	Weinig O	Veel O	Heel veel O

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Appendix D: Coding Table

Coding table

No influence	Room for extracurricular material
	Attitude of teachers
	Resources
Influence only by course development	Practicality teachers
	Motivation of students - Curiosity - Relevance
	Active Learning
	21st century skills - Efficient teamwork - Critical thinking
Influence inherent to biomimicry	Multidisciplinarity
	Open problems and questions
	Teacher is a coach
	Formative assessment
	Societal Themes - Sustainability - Citizenship & System thinking
	21st century skills - Creativity - Problem solving - Analytical thinking