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# Learning eco-innovation from nature: an interdisciplinary approach to education in systematic environmental innovation

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## CONTEXT

Ecological challenges associated with the global economic development have intensified the need for university graduates that are capable of rapidly finding environmental-friendly solutions to complex problems and can successfully implement eco-innovative concepts. As major negative implication of the technological progress is attributable to its environmental impact, numerous approaches and methods have been developed in the last three decades to support sustainable and eco-friendly product and process development, such as Life Cycle Assessment, Eco-Design, Green Engineering and others. However, engineering curricula still contain too few offers for a structured eco-innovation and development of new solutions providing significant environmental advantages.

## PURPOSE OR GOAL

As engineering graduates and specialists frequently lack the advanced skills and knowledge required to run eco-innovation systematically, the paper proposes a new learning materials and educational tools in the field of eco-innovation and evaluates the learning experience and outcomes. This programme is aimed at strengthening student's skills and motivation to identify and creatively overcome secondary eco-contradictions in case if additional environmental problems appear as negative side effects of eco-friendly solutions. The paper evaluates the efficiency of the proposed interdisciplinary tool for systematic eco-innovation including creative semi-automatic knowledge-based idea generation and concept development. It analyses the learning experience and identifies the factors that impact the eco-innovation performance of the students.

## APPROACH OR METHODOLOGY/METHODS

Based on a literature analysis and own investigations, authors introduce a manageable number of eco-innovation heuristics with particular focus on the identification of underlying eco-inventive principles used in the natural systems created through evolution. Finally, the paper proposes a comprehensive method for capturing eco-innovation principles in biological systems in addition and complementary to the existing biomimetic methods and other eco-innovation approaches. It shares the experience in application of eco-innovation tools at the Offenburg University, involving students from different years of study and with different knowledge levels.

## ACTUAL OR ANTICIPATED OUTCOMES

The proposed educational approach equips students with the advanced knowledge, skills, and competences in the field of eco-innovation. Analysis of the student's work allows one to recommend simple-to-use tools for a fast application in process engineering, such as for example strongest inventive operators for solving of environmental problems. For the majority of students in the survey, even the small workload has strengthened their self-confidence and skills in eco-innovation.

## CONCLUSIONS/RECOMMENDATIONS/SUMMARY

The proposed interdisciplinary eco-innovation tool can be integrated in the discipline-specific subjects and can be recommended for specialists, engineering educators, and creators of eco-innovation methods.

## KEYWORDS

environmental education, eco-innovation, sustainability, biomimetics, TRIZ

# Introduction

Ecological challenges associated with the global economic development have intensified the need for university graduates that are capable of rapidly finding environmental-friendly solutions to complex problems and can successfully implement eco-innovative concepts. Numerous approaches and methods have been developed in the last three decades to support sustainable and eco-friendly product and process development, such as Life Cycle Assessment LCA (ISO14040:2006), Eco-Design, Green Engineering, Process Intensification, Process Design for Sustainability, and others. The International Standard Organization defines Eco-Design as “integration of environmental aspects into product design and development, with the aim of reducing adverse environmental impacts throughout a product's life cycle" (ISO 14006:2011). The eco-innovation focuses on the integration of environmental aspects and requirements in the early stages of the innovation processes for new product or technology development to provide significant environmental advantages.

However, these methods frequently don’t belong to the mandatory components of engineering studies today. Moreover, the existing discipline subjects in engineering curricula still contain too few offers for a structured eco-innovation and development of new solutions providing significant environmental advantages. There is often a gap between the students’ competences in sustainable and environmentally friendly product and process development obtained at the engineering universities and the needs of industrial companies and society (Olsen et al., 2018). On the other hand, there is strong evidence that academics can effectively embed teaching eco-innovation heuristics into their existing discipline-based subjects, applying the so-called “infusion” interdisciplinary teaching approach (Belski et al., 2018) to improve creativity and eco-innovation skills of students.

Many researchers, such as e.g., Boodhoo & Harvey (2013), propose to apply the knowledge-based engineering methods of the Process Intensification to overcome negative environmental impacts. Russo et al., (2017) offer 250 eco-innovation guidelines. The Theory of Inventive Problem Solving TRIZ (VDI, 2016) as a comprehensive knowledge-based innovation methodology offers systematic approach and tools for identification and elimination of negative ecological effects. A systematic review of eco-innovation creativity tools based on TRIZ is provided by Livotov et al (2019a). Today, the biomimetics or biomimicry belongs to the established approaches to design for innovation and sustainability (Benyus, 1997). Helfman Cohen and Reich (2019) give a detailed review of current biomimetic design methods for transferring design solutions from nature to technology.

Maccioni et al (2019) analyse 66 eco-design principles and outline that despite the potential to enhance the environmental performance not all eco-design principles lead to the market success due to the secondary problems or engineering contradictions. Russo et al (2015) outline that identification of the engineering contradictions is one of the important aspects in eco-design. In this context, two types of eco-engineering contradictions can be defined in engineering systems: primary contradiction and secondary contradiction. A primary eco-engineering contradiction occurs when the improvement of a non-ecological engineering parameter (e.g. productivity) leads to a deterioration of an environmental characteristic in process or equipment (e.g. air pollution), or vice versa. Consequently, a secondary eco-engineering contradiction is a situation where the improvement of one ecological parameter causes the worsening of another ecological parameter.

In their previous work in the field of engineering education in eco-innovation in process engineering (Livotov et al., 2019b) the authors proposed a number of eco-innovation tools with particular focus on the identification of eco-problems in existing technologies, selection of the appropriate new technologies (knowledge-based engineering), and systematic ideation and problem solving (knowledge-based invention), which are presented in Table 1 (pos. 1-7). Educators can apply one or several tools for their courses depending on time availability, competencies, and skills to be learned or improved, using their own examples or problems. The explanation efforts of educators are considered as low – if a tool requires up to 10 minutes introduction and its application is almost self-explanatory. The medium efforts correspond to 30 minutes introduction with examples and high efforts correspond as a rule to a two-hour introductory seminar in which the educator has to guide students in each step of the learning process.

In the current paper the authors want to offer two additional eco-innovation tools that could be taught in the stand-alone subjects on sustainability and eco-innovation or through their integration into existing discipline-based subjects. The first analytical method (Table 1, pos. 8) allows one to systematically identify eco-innovation solution principles through analysis of biological systems living in hostile environment. The second creative tool (pos. 9) represents the further development and sematic adaptation of the TRIZ inventive principles (pos. 7) known in the TRIZ methodology for a fast automated idea generation.

**Table 1: Eco-innovation tools for integration into the engineering subjects**

| N | Eco-innovation tool | Application field (skills) | Explanation efforts of educator |
|---|---|---|---|
| 1 | Identification of eco-engineering contradictions | Problem definition and analysis | medium |
| 2 | Process mapping incl. resources analysis | | high |
| 3 | Ecological Anticipatory Failure Identification | Problem definition and analysis, engineering creativity | medium |
| 4 | Sustainable process intensification technologies (database) | Knowledge-based engineering | medium |
| 5 | Nine fields heuristic MATCHEM-IBD | Engineering creativity, knowledge-based innovation and invention | low |
| 6 | Five cross industry analogies | | low |
| 7 | TRIZ Inventive operators | | medium |
| 8 | Biomimetic approach for identification of natural eco-innovation principles | | high |
| 9 | Automated idea generation with TRIZ inventive operators | | medium |

# Identification of the Natural Eco-Innovation Principles

It can be assumed that the existing biological systems sparingly utilize energy and material resources and have a lesser additional environmental impact, as compared to the human-made products or technologies. Moreover, hundreds of millions of years of evolution have resulted in “natural” sustainable technologies and underlying abstract eco-innovation principles, which can be helpful for problem solving not only in environmental engineering. Such biological innovation principles are termed here as “natural” eco-innovation principles. For example, some orchids and other plants in arid regions have a particular form of CAM-photosynthesis, which allows to reduce their water consumption by 80%, by shifting the carbon fixation phase into the night period with low humidity losses (Zhang, 2016). The derived natural inventive principle here is *accumulation of energy or substances in advance*. Vincent (2017) gives examples of natural inventive principles such as *dynamic equilibrium*, *acclimatization*, or *genotypic change*. Since biological systems, defined as systems of/with living biological organisms, are usually more complex than engineering systems, the technology transfer from nature to engineering requires interdisciplinary knowledge and appropriate tools. For example, the *Ask Nature* database of the Biomimicry Institute (Ask Nature, 2021) documents more than 1700 strategies developed by natural systems that achieve different functions. Besides retrieval and analysis of existing bio-inspired eco-friendly technologies or biological strategies from the literature or databases, the identification of the natural principles for eco-innovation can be carried out using problem-driven or solution-driven approaches.

The problem-driven approach can use different algorithms and the function-oriented search to find a biological or natural solution for existing environmental problem. Helms (2009) defines the key phases of this approach: 1 - problem definition incl. functional decomposition, 2 - reframing the problem in universally applicable biological terms, 3 - biological solution search with a set of heuristics, 4 - definition of the biological solution, 5 - extraction of solution principle in an abstract form, 6 - application of solution principle. The solution-driven approach analyses first a biological solution, reframes it in universally applicable engineering terms, and identifies a corresponding engineering problem for solving with the biological solution principle. The authors have made positive experiences with both approaches in introducing eco-innovation tools in Bachelor and Master courses. However, the problem- and solution-driven approaches can be augmented in the field of eco-innovation with a targeted search for biological eco-systems operating under environmental stress, such as for example, high or low temperatures, extreme sun radiation, arid regions, toxic substances etc. Such restriction of the search field makes the biomimetic eco-innovation design process more efficient and targeted and lessens the workload of the students. Table 2 exemplarily presents main steps of the biomimetic approach to eco-innovation for a predefined eco-engineering problem applied in the educational courses.

**Table 2: Biomimetic approach to eco-innovation for a predefined eco-engineering problem**

| Process phase | Description |
|---|---|
| 1. Identification of possible biological solutions | 1.1. Definition and classification of environmental stress factors relevant for the pre-defined eco-engineering problem.<br>1.2. Systematic search for biological eco-systems exposed to environmental stress. |
| 2. Analysis and definition of the biological solutions in identified eco-systems | 2.1. Component and function analysis for the eco-system, its sub-systems (bio-components) and super-system.<br>2.2. Identification of contradictory functions and eco-requirements.<br>2.3. Identification of the bio-components responsible for resolving of eco-contradictions between opposing functions or requirements. |
| 3. Extraction of biological solution principles in biological terms | 3.1. Extraction of concrete biological eco-solutions in the bio-components identified in step 2.3.<br>3.2. Formulation of abstract biological eco-solution principles in biological terms. |
| 4. Reframing biological solution principles in universally applicable abstract engineering terms | 4.1. Transformation of abstract biological solution to eco-engineering using universally applicable technical terms.<br>4.2. Definition of the underlying abstract engineering solutions and abstract natural inventive principles.<br>4.3. Assignment of the inventive principles to the corresponding eco-contradictions. |
| 5. Application of the biological principles and development of the bio-inspired engineering solution | 5.1. Development of bio-inspired eco-solution (product or process).<br>5.2. Anticipation of possible new secondary problems and eco-contradictions.<br>5.3. Optimization of existing eco-solution or application of other biomimetic inventive principles and solutions. |

Vincent (2017) outlines that a trade-off between two contradicting requirements belongs to a central concept of biomimetics. Using the function analysis in the phase 2, it is essential to identify all bio-components with their functions and strategies for adaptation to unfavourable or hostile environment. Trade-offs, conflicts of goals or eco-contradictions identified and explored at step 2.2 can point towards possible concealed bio-solutions. For example, for a plant in arid regions, the reduction of water losses by transpiration and larger leaf surface area for photosynthesis build a pair of contradictory requirements. The surface structure, form, position, colour, biochemistry, or other properties of the plant leaf could give an answer, how a bio-system responds to this challenge.

The following example illustrates the application of the eco-innovation tool to a problem of the coastal erosion protection. In accordance with Flowers and Colmer (2017) mangroves are salt-tolerant trees, also called *halophytes*, adapted to life in hostile environment under the low oxygen conditions. They contain a complex salt filtration system and complex root system to cope with saltwater immersion and wave action. Van de Riet (2019) explored how the irregular mangrove root's structure reduces turbulences in coastal area and proposed geometrically similar artificial barriers as a solution to prevent the coastal erosion. The identified eco-innovation principles for the given problem are a) application of irregular structure in hydrodynamic systems and b) reduction of turbulences.

In the context of the further procedure, table 3 illustrates the application of the solution-driven biomimetic approach on example of mangroves. The eco-innovation principles are extracted by functional analysis of bio-components. Most students use enthusiastically the creative solution-driven approach in the courses and believe to employ it in their graduation theses later.

**Table 3: Examples of eco-innovation principles identified in the mangroves eco-system**

| Bio-component | Function | Natural inventive principles |
|---|---|---|
| Pneumatophores | Absorbing oxygen from the air and water: pipe-like structures sticking out of the mud act like snorkels | Simultaneous absorption of substances from gas and fluid |
| Roots and stems | Mangrove roots and stems have special tissues which act as a barrier to salt | Use in parallel different technologies to block or extract harmful agent |
| Fresh leaves | Extraction of the salt underneath the mangrove leaves: special glands concentrate salt and excrete it to the surface | Use different sides or parts of an object for competing operations: extraction of salt and photosynthesis |
| Leaves, flowers, fruits | Concentrating and removal the salt: salt can be moved to old leaves, flowers, or fruits which then drop off, taking the concentrated salt with them | Apply biodegradable waste to remove harmful substances |
| Seeds | Protect reproductive function from environment: seedlings germinate, and start developing on the tree and survive in seawater for year or more | Isolate sensitive processes from hostile environment in time and in space |

Our practical experience confirms that the identification of eco-innovative solution principles in biological systems adapted to hostile environment enhances both the creativity and the systematic way of inventive thinking. However, its application requires moderate to significant workload that can limit its integration into existing discipline-based subjects. Generally, a creation of the database of the natural eco-innovation principles, extracted from biological systems and strategies, can be considered as a promising direction of innovation research.

## Automated Idea Generation for Eco-Innovation

As experimentally confirmed by Belski et al (2018) the inventive principles and heuristics of the Theory of Inventive Problem Solving TRIZ (VDI, 2016) help systematically enhance the ideation performance of students and specialists. One of the latest enhanced versions of the 40 Inventive Principles, as one of most frequently used TRIZ heuristic, has been proposed by the authors (Livotov et. al, 2019a) and contains 160 inventive elementary sub-principles for idea generation. This version is continuously complemented and extended with recently identified natural eco-innovation principles as described in previous section of the paper. Based on meticulous analysis of 155 new technologies, 200 patent documents, numerous industrial case studies and scientific literature the authors identified the statistically strongest elementary inventive for eco-innovation and eco-design in general and for reduction of energy and material consumption and losses in particular. These recommendations allow one to select from 160 inventive sub-principles the 15…30 statistically strongest inventive heuristics for fast and targeted idea generation.

However, a practical application of inventive principles often requires a concentrated, creative, and abstract way of thinking that can be challenging especially for newcomers to TRIZ. For example, the abstract term “object” used in the principles may be understood as a system, system component, substance, process or process step, or any other material or virtual object. Also, the abstract definition of “action” can be understood as function, positive or negative effect or any interaction between the objects. Therefore, the outcomes of ideation work depend on a certain interpretation of the abstract terms.

Moreover, some of the inventive operators are more specific and can be clearly assigned to at least one of nine MATCEM-IBD engineering domains: M - Mechanical, A - Acoustic, T - Thermal, C - Chemical, E - Electrical, M - Magnetic, I - Intermolecular, B - Biological and D – Data or Information processing. On the other hand, there is also a group of generally formulated *universal* inventive operators, which are independent of any engineering domain and hence could require additional analysis and reflection by their use. A part of the universal operators forms a group of the inventive operators for Design.

The experimental study carried out by the authors confirms that the less abstract and problem specific formulation of TRIZ inventive principles can visibly improve idea generation outcomes of engineering students both in the quantity of ideas and their variety. The breadth over the nine MATCEM-IBD domains has been essentially enhanced while applying the less abstract principles. In 194 experiments conducted at the Offenburg University the students generated nearly 1.5 times more ideas with the semantically modified and thus less abstract inventive principles than with the classically formulated TRIZ Inventive principles. This positive effect was observed by the students from different years of study independently of their knowledge level or difficulty of the problem.

In order to make the application of inventive principles faster and easier for the students without prior skills in TRIZ, authors propose a semantic transformation defined as a collection of rules that specify how inventive principles can be represented in a less abstract form as a finite number of automatically generated solution ideas. In accordance with (Livotov, 2021), in order to initiate the automated ideation for a pre-defined problem, it is only necessary to formulate the following problem-specific categories: Working tool, Target object (affected by the working tool), Useful action, Harmful effect. The semantic transformation then generates up to 170 solution ideas distributed over the problem definition categories as follows: Working tool (83 ideas); Target object (30 ideas), Useful action (47 ideas), Harmful effect (10 ideas). In the practice, the top 15…30 automatically generated ideas with the highest statistical ranking deliver at least 3…6 workable solutions of the eco-engineering problem.

Table 4 illustrates the outcomes of the automated idea generation for the problem on how to reduce the energy transfer losses of the wireless inductive charging of the smartphones. It presents exemplarily 7 of 50 ideas with the high statistical ranking for reduction of energy losses out of total of 170, with the *inductive coil* as working tool, *smartphone* as target object, wireless *energy transfer* as useful action, and *energy losses* as harm. A systematic identification of high-quality and rapidly implementable solution ideas can be performed in accordance with their engineering domains, low to medium abstraction level and higher statistical ranking. Table 4 also illustrates how the automatically generated ideas are assigned to the engineering domains.

**Table 4: Automatically generated ideas to reduce transfer losses of the wireless charging**

| Automatically generated solution ideas | Abstraction level | Engineering domain |
|---|---|---|
| Change mechanical or surface properties of inductive coil like density, roughness, strength etc. | Medium | Mechanical |
| Change electrical, magnetic, or electromagnetic properties of inductive coil like conductivity, magnetism etc. | Medium | Electro-magnetic |
| Pre-arrange inductive coil so it can come into action at the most convenient position and without losing time | Medium | Universal |
| Divide inductive coil into several independent adjustable parts or sections. | Low | Design |
| Remove the disturbing parts or substances from the smartphone responsible for energy losses | Medium | Design |
| Change the temperature of smartphone by heating or cooling | Low | Thermal |
| Apply automatic control and artificial intelligence to optimize wireless energy transfer | Medium | Digitizing |

# Concluding Remarks and Outlook

There is a scientific and practical demand to structure the existing and continuously growing body of knowledge in the field of eco-innovation, including best practices, examples of case studies, etc. The authors argue that the enormous potential of biomimetics for eco-innovation is not yet fully exploited. Therefore, the presented paper advocates the need for identification of new abstract biological inventive principles for eco-innovation. The future research should be focused on creation of the database of natural abstract eco-innovation principles complementary to the inventive principles known in the TRIZ methodology and other approaches to the knowledge-based innovation for promoting, sharing and reuse of innovation knowledge.

The proposed educational tools equip students with the advanced knowledge and competences in the field of eco-innovation. For many students in the survey, even the small workload has strengthened their self-confidence and skills. The authors also wish to suggest that engineering educators need to consider embedding the proposed tools into their professional activities. The future research should be focused on further development of learning resources, such as standard guidelines, interdisciplinary examples, best-practice recommendations, and on further optimization and computerization of the educational eco-innovation toolbox.

## References

Ask Nature (2021). Biological strategies. Retrieved July 20, 2021, from https://asknature.org/biological-strategies/

Belski, I., Skiadopoulos, A., Aranda-Mena, G., Cascini, G., Russo, D. (2018). Engineering Creativity: the Influence of General Knowledge and Thinking Heuristics. In L. Chechurin & M. Collan (Eds.), Advances in Systematic Creativity (pp. 245-263). McMillan.

Benyus, J. M. (1998). *Biomimicry: Innovation Inspired By Nature*. New York: HarperCollins.

Boodhoo, K.V.K., Harvey, A. (2013). Process intensification: an overview of principles and practice. In K.V.K. Boodhoo, A. Harvey (Eds.), Process Intensification for Green Chemistry: Engineering Solutions for Sustainable Chemical Processing (pp.1-31). John Wiley.

Flowers, T. J., Colmer, T. D. (2015). Plant salt tolerance: adaptations in halophytes. *Annals of Botany 115*(3), 327–331.

Helfman Cohen, Y., Reich, Y. (2016). *Biomimetic Design Method for Innovation and Sustainability*. Springer Int. Publishing, Switzerland.

Helms, M. (2009). Biologically Inspired Design: Process and Products. *Design Studies 30*, 606-622.

Livotov, P., Chandra Sekaran, A.P., Mas'udah, Law, R., Reay, D., Sarsenova, A. & Sayyareh, S. (2019a). Eco-innovation in Process Engineering: Contradictions, Inventive Principles and Methods. *Thermal Science and Engineering Progress*, *9*, 52-65.

Livotov, P., Mas'udah, Chandra Sekaran, A.P., Law, R., Reay, D. (2019b). Education in systematic eco-innovation in environmental and process engineering. Paper presented at the Australasian Association for Engineering Education Annual Conference, Brisbane.

Livotov, P. (2021). Method for Formulation, Selection and Application of Elementary TRIZ Inventive Principles for Automated Idea Generation. In: Borgianni Y., Brad S., Cavallucci D., Livotov P. (eds) Creative Solutions for a Sustainable Development. TFC 2021. IFIP Advances in Information and Communication Technology, vol 635 (pp. 315-329). Springer, Cham.

Maccioni, L., Borgianni, Y. & Pigosso, D.C.A. (2019). Can the choice of eco-design principles affect products' success? *Design Science, Vol. 5*, 1-31. DOI: 10.1017/dsj.2019.24

Olsen, S. I., Fantke, P., Laurent, A., Birkved, M., Bey, N. & Hauschild, M. Z. (2018). Sustainability and LCA in Engineering Education - A Course Curriculum. *Procedia CIRP*, *69(5)*, 627–632.

Russo, D., Serafini, M. (2015). Anticipating the identification of contradictions in eco-design problems. *Procedia Engineering 131*, 1011–1020.

Russo D., Rizzi C., Spreafico C. (2017) How to Build Guidelines for Eco-Improvement. In: Campana G., Howlett R., Setchi R., Cimatti B. (Eds.), *Sustainable Design and Manufacturing*. *Smart Innovation, Systems and Technologies* (pp. 879-887), Springer, Cham.

Van de Riet, K. (2019). Biomimicry of Mangroves Teaches How to Improve Coastal Barriers. Retrieved August 02, 2021, from https://www.ansys.com/blog/biomimicry-mangroves-improve-coastal-erosion-coastal-barriers

VDI Standard 4521. (2016). *Inventive problem Solving with TRIZ. Fundamentals, terms and definitions*. Beuth publishers, Duesseldorf, Germany.

Vincent, J. (2017). The Trade-off – A Central Concept for Biomimetics. *Bioinspired, Biomimetic and Nanobiomaterials 6*(2), 67-76.

Zhang, L., Chen, F., Zhang, G.-Q. et al. (2016). Origin and mechanism of Crassulacean acid metabolism in orchids as implied by comparative transcriptomics and genomics of the carbon fixation pathway. *Plant Journal 86*(2), 175-185. doi: 10.1111/tpj.13159.

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