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What can we learn from biological systems when applying the law of system completeness?

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Abstract

Biological systems have been evolving for millions of years while technical systems have been evolving for only a few hundred years. Are biological systems architectures and functions similar to those found in technical systems or are they different systems altogether?
Biological Systems were analyzed in terms of the Law of System Completeness: engine, transmission unit, working unit and control pattern structures plus sources and forms of energy transmitted. The analysis shows several interesting insights in terms of sustainability aspects such as: (1) Biological systems use external energy sources almost without any extra cost by adopting ready available environmental resources. (2) In biological systems, essential elements, such as the working unit or the control unit, may be provided by elements and components from their surrounding environment. (3) Analysis of biological systems using the law of system completeness provides an operational language that eases the description of those systems and improves their understanding. The examples provided in this study contribute to a better understanding of biological systems and can be further used as guidelines to drive innovative designs of sustainable technical systems.

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Keywords: Law of system completeness, Natural systems, Technical systems, Energy source, Sustainability;

1. Introduction

Biological systems have been evolving for millions of years while technical systems have been evolving for only a few hundred years. Are biological systems architectures and functions similar to those found in technical systems or are they different systems altogether?

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There are major differences between biological and technical systems. Technical systems are designed by humans for performing functions; biological systems evolve with their genetic codes governed by natural selection. The definition of the terms function, behavior and performance in these systems is distinctive and requires further elaboration that is beyond the scope of this paper.

In this study, when we use the word function in relation to technical systems we refer to the required result of the design, the goal of the creation of the system, which is aimed to be identical to the system behavior (what the system actually does). In biological systems, we keep in mind that the mechanism that had led to create a specific function was not predetermined or planned in advance and can be sometimes be a random genetic evolutionary change. Therefore, we can't claim that the function is the result of the design, as we claimed for technical systems. However, in biological systems we can identify what they actually do. Therefore, when we use the word function in relation to biological systems we refer to an interpretation of the system actual behavior or of the work that it does.

From a sustainable point of view, technical systems operate within wide conditions; biological systems operate within restricted living constraints and therefore avoid high temperatures, strong pressures or toxic materials. Biological systems are more coordinated with the environment and therefore offer a promising potential to learn sustainable design principles.

One of the major challenges of humanity today is to adapt our technology to become more sustainable. Nowadays technical achievements are impressive, but it now becomes imperative to look at other aspects of performance like sustainability.

The main motivation for performing this study is to learn sustainable design principles from biological systems and transfer them to technical systems by using biomimetic processes. Biomimicry is a multidisciplinary discipline that studies nature's best ideas for imitating these designs and processes to solve human problems in a sustainable and innovative ways [1]. Learning from nature results in finding new design concepts and mechanisms. Natural systems provide wide range of environmental adaptation patterns that can be further used to overcome technical challenges and promote innovation and sustainability levels of the design concepts.

In this study, we use the Law of System Completeness for analyzing the architecture of biological systems that can be further applied for designing new sustainable technologies.

2. TRIZ, Sustainability & Biological Systems

TRIZ has already been identified as a main core of knowledge suitable for bridging the gap between biology and engineering. This transfer process between domains benefits both our understanding of biological systems and enlarges TRIZ knowledge with new biological inventive principles.

Altshuller himself identified the potential of exploring the 3.8 billion years of natural design lab to improve and enrich the TRIZ Method [2]. But Alltshuller's vision was not fulfilled until the latest study of the BioTriz [3], as most of the TRIZ knowledge until then was based on different fields of engineering including physics, chemistry, and mechanical engineering, with no reference to the biological basis of knowledge. About 3000 biological phenomena were analyzed by the BioTRIZ research team in an effort to identify biological solutions to engineering conflicts. Contrary to the basic TRIZ matrix, which contains 40 engineering parameters, the new BioTRIZ matrix is condensed and includes only 6 categories, organized by the following principle: Things (substance, structure) do things (requiring energy and information) somewhere (space, time). One of the BioTRIZ Interesting findings from a sustainable point of view is that technology tends to solve problems by using energy and matter, while in nature problems are mostly solved by using structure and information, which consume less energy and matter [3]. The BioTRIZ study led to a better understanding of natural sustainable strategies for solving design conflicts. Other studies used some different basic TRIZ tools besides the contradiction matrix to develop eco-design tools and frameworks for sustainable design. Russo et al. [4] used some TRIZ tools such as Ideality, Resources and Laws of technical evolution, to form several practical eco-guidelines for product innovation and sustainability. They claimed that TRIZ tools benefit EcoDesign mainly by providing guidelines to increase product sustainability and a better usage of resources, and that TRIZ tools extend the way we evaluate resources taking into consideration their contribution to the system function and their potential effects with other super-system factors. D'Anna & Cascini [5] offered the SUSTAINability map, a new approach towards the preliminary analysis of sustainability problems. It is based on two basic TRIZ tools: the Laws of Evolution of Engineering Systems and the System Operator.

In this study, we use another TRIZ tool, the Law of System Completeness, in order to gain more understanding about sustainable design principles.

3. The Law of System Completeness

Together with the contradiction matrix, there are some other prominent TRIZ Tools. Among them are the system technical evolution laws proposed by Altshuller for technical system evolution. One of these evolution laws is the "Law of System Completeness." This law describes four essential elements of a technical system: engine, transmission unit, working unit and a control unit. The law requires that all components are present and that if any component fails or is missing, the system does not survive [6]. Savransky [7] added a fifth essential element, the casing, which protects technical system and the environment from each other, provides safety and maintains the structure and shape of the technical system. The contribution of this law to our understanding of technical and business systems has already been demonstrated [8, 9], where the law enhanced understanding of the system structure and identified ways to improve it.

In this paper, we examine biological systems using the "Law of System Completeness". Will we gain a better understanding of biological systems structure as we gained for technical and business systems? As far as the authors know, an analysis of biological system by the law of system completeness has not been studied yet. In the first step of analysis, we aim to create better understanding of the structure and sustainable aspects of biological systems. In the next step, we would like to use this knowledge to extract relevant design principles.

4. The Method of Analysis

We analyzed dozens of biological systems according to the Law of System Completeness. We focused on biological systems that are already related to biomimetic designs, as the main motivation of this study is to learn sustainable design principles from biological systems that can be further transferred to technical systems by biomimetic design processes.

The biological systems were analyzed in terms of the law of system completeness to find their: engine, transmission unit, working unit and control pattern structures plus source and forms of energy transmitted. We placed the working unit in a physical contact with the target object according to the definition of a working unit [10] and formulated the ten stages analysis procedure as shown in Table 1.

As definitions of super-system and sub-system depend on the context and functionality, we will clarify that in our analysis, system boundaries are defined as the physical boundaries of the organism; the body casing. The system is the organism itself; sub-system parts are internal biotic organs or parts of the organism; super –system parts are environmental elements outside the organism body casing which may be in the living surrounding of the organism.

The ten stages analysis procedure (Table 1) was developed using the above definition of the system boundaries. This procedure may direct the results of an analysis, but we may not expect only one exact result as different users have different levels of knowledge about the system. Different point of views may foster creativity, and the vitality of this procedure should be examined at the personal level: Does this process led to a better understanding of the system structure, dynamics, control and design patterns?

5. Analysis Results

The analyses of dozens of systems revealed that biological systems could be classified into one of four types of systems that are defined by the following parameters:

Type of working units:

Environmental working unit –Working unit is provided by environmental parts or elements (Outside the organism body casing).

Non-Environmental working unit – Working unit is provided by internal biotic organs or parts of the organism.

Type of control unit:

Environmental control unit (Positive feedback) – Positive feedback is a “feedback that tends to magnify a process or increase its output” (Miriam- Webster). System parameters are changed in a certain direction and there is no need to change this direction or to "switch" between different system conditions. As there is no need to control the direction of change, control is being done by environmental conditions.

Non-Environmental control unit (Negative feedback) –Negative feedback is a “feedback that tends to dampen a process by applying the output against the initial conditions” (Miriam-Webster). System parameters are stable in a certain range and might be switched within this range according to different system conditions. As a result, there is a need to control and eliminate parameter changes. In order to gain this required control, control unit is part of the organism itself and not part of the environment.

The combination of these two parameters is presented as a typology of biological systems in Table 2.

Table 1: The ten stages procedure for the Law of Systems Completeness analysis

	Analysis procedure questions	The Law of System completeness parts	Remarks
1	Identify the main function of the system.	System Function	
2	Which is the target object of this function?	Target Object	
3	Identify system parts: System, Super- system, Sub-system	System Parts	
4	Which Parts of system physically touch the target object?		
5	Which part of the system performs the function?	Working-Unit	The working unit is in physical touch with the target object.
6	Which are the system parameters that are changed by the working unit?	System Parameters	
7	Which Source of energy is used to perform the function?	Source of Energy	
8	Which part of the system converts this source of energy to work?	Engine	
9	Which part of the system transfers this energy to the working unit?	Transmission Unit	
10	How does the system parameter change?	Control Unit type	Does the parameter change in a certain direction? (positive feedback) Is it stable in a certain range? (Negative Feedback).

Table 2: Sustainable structures typology of biological systems according to the Law of Systems Completeness

	Environmental control unit (Positive Feedback)	Non-Environmental control unit (Negative Feedback)
Environmental working unit	The **working unit** is provided by environmental parts or elements. Work is done by the interactions of the biological systems and the environmental element. The changeable parameter is enhanced in a certain direction. **Control** is done by environmental conditions.	The **working unit** is provided by environmental parts or elements. Work is done by the interactions of the biological systems and the environmental element. System parameters are stable in a certain range and might be switched within this range according to different system conditions. **Control unit** is part of the organism itself and not part of the environment.
Non-Environmental working unit	The **working unit** is provided by internal biotic organs or parts of the organism. The changeable parameter is enhanced in a certain direction. **Control** is done by environmental conditions.	The **working unit** is provided by internal biotic organs or parts of the organism System parameters are stable in a certain range and might be switched within this range according to different system conditions. **Control unit** is part of the organism itself and not part of the environment.

6. Examples of each system type

6.1. Environmental working unit with a positive feedback: The Lotus effect cleaning mechanism.

Description of the mechanism: Dirt particle removal by a water droplet is a stepwise process. There is a need to attach the dirt particle to the water droplet and then to move the water droplet accompanied with the dirt particle away from the leaf.

The Lotus leaf (Nelumno nucifera) structure is full of small epidermal protrusions covered with wax at the nanometer range (see Fig. 1). These protrusions create high contact angle between the surface and the droplet resulting in a reduced contact area and a reduced adhesion force between the surface and the droplet. The droplet gets a spherical shape and rolls down the slope of the leaf under the influence of gravity. If it rolls across a dirt particle, the droplet collects it, as the adhesion between the dirt particle and the droplet is higher than the adhesion between the dirt particle and the leaf surface [11]. In the following analysis we focus on the first step of the collection of dirt particles by adhesion forces and ignore the second step of the droplet rolling down with the dirt particle under gravity.

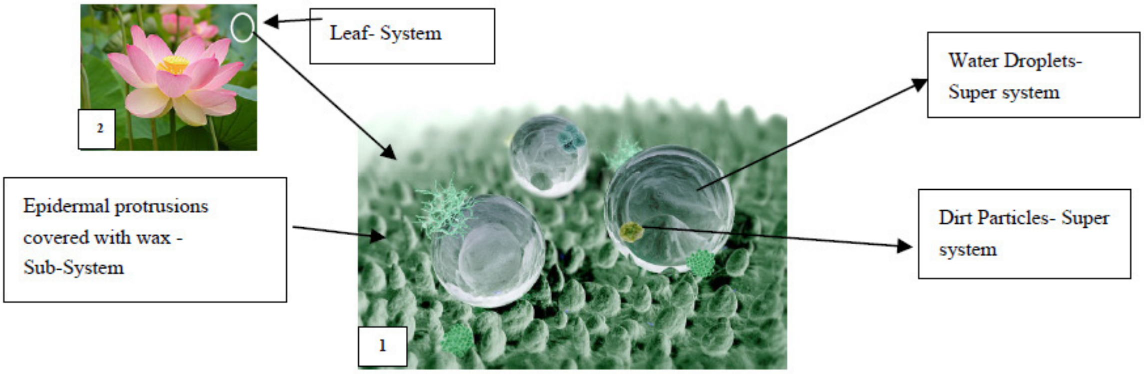

Fig 1: The lotus effect cleaning mechanism
Photo 1 by William Thielicke from Wikimedia under GNU Free Documentation License, Version 1.2
Photo2 by Peripitus adapted from Wikimedia under GNU Free Documentation License, Version 1.2

The ten stages analysis procedure for this example is described in Table 3. The resulting system diagram is shown in Fig. 2. The bold solid lines show the system parts within its physical boundaries while the dashed lines depict the system parts that belong to the environment. Each box is denoted with its role in the system. This template is used in subsequent examples.

As shown in Fig. 2, the water droplets, environmental elements, perform the work of moving the particles. Control is done by environmental conditions as the work is based on the presence of water and particles in the environment. This control is based on a positive feedback as the dirt particles are changed in a certain direction towards total removal.

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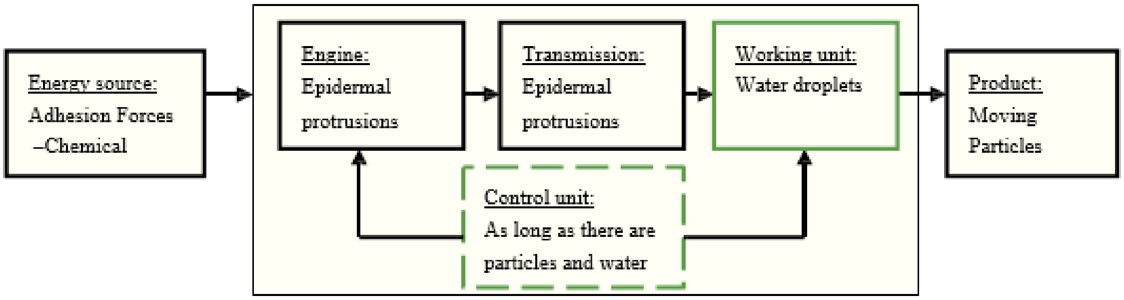

Fig. 2. Lotus effect cleaning mechanism- analysis by the law of system completeness

6.2. Environmental working unit with a negative feedback: Gecko's feet adhesion mechanism

Description of mechanism: Gecko's foot has nearly five hundred thousand hairs or setae (see Fig. 3). Each individual setae is connected to the surface by van der Waals forces. Multiplying the connection force of each setae by the total numbers of setae creates a strong connection. When the gecko changes the foot's contact angle with the surface, these van der Waals forces disappear. The foot is switched between two situations: Attached / Detached to the surface [12].

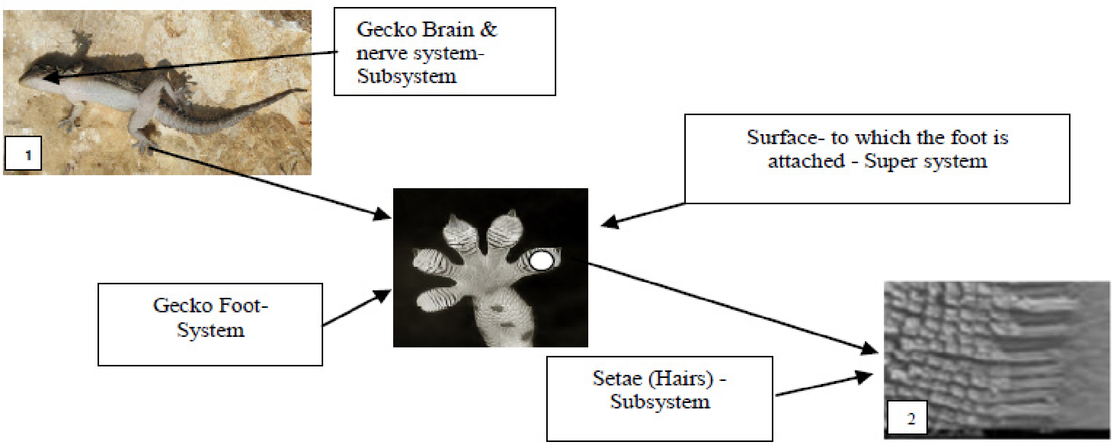

Fig 3: The gecko's feet adhesion mechanism.
Photo 1 by Yanpetro adapted from wikimedia under GNU Free Documentation License, Version 1.2
Photo 2 by Kellar Autumn [12], reproduced with permission of the copyright owner.

The ten stages analysis procedure for this example is described in Table 3. The resulting system diagram is shown in Fig. 4. As shown in Fig. 4 the interaction between the setae and the surface, an environmental element, performs the work of attaching and detaching the foot. The control unit is part of the organism itself, the gecko's nerve system. This control is based on a negative feedback as the system is switched between two different positions: attached foot and detached foot while the number of setae in contact with the surface is enlarged or reduced in certain rang.

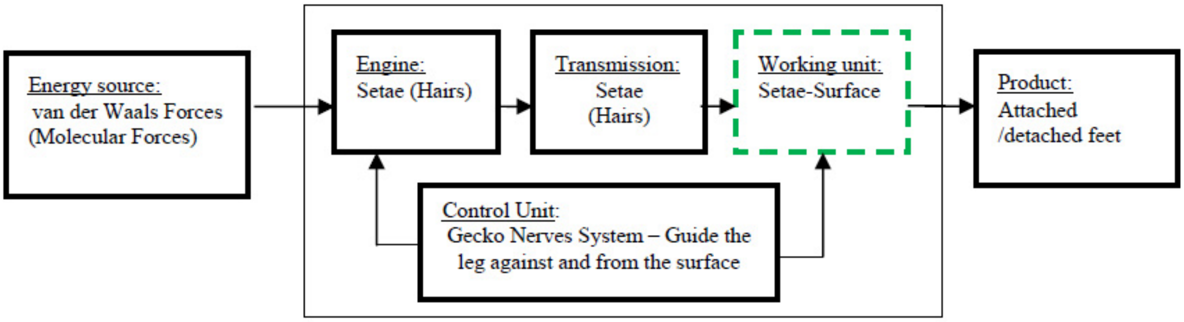

Fig. 4. Gecko's foot adhesion mechanism - analysis by the law of system completeness

6.3. Non- Environmental working unit with a positive feedback- The Abalone Shell Pressure absorption mechanism

Description of mechanism: The shell of the abalone is combined of alternating hard layers made of microscopic calcium carbonate and soft layers made of protein substance (see Fig. 5). It is a perfect example of a composite material. When the abalone shell is exposed to external pressure, the hard layers slide instead of breaking and the protein stretches to absorb the energy of the blow. The protein acts like "rubber" and has enormous capacity to absorb shock without breaking [13].

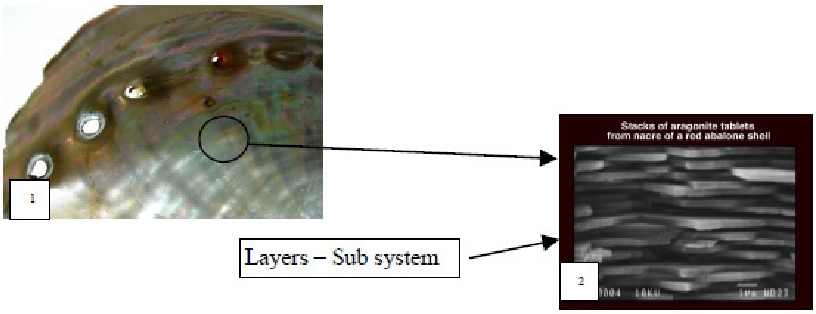

Fig 5: The Abalone Shell Pressure absorption mechanism.
Photo 1 by N yotaro adapted from wikimedia under GNU Free Documentation License, Version 1.2
Photo 2 by Paul Hansma [13], reproduced with permission of the copyright owner.

The ten stages analysis procedure for this example is described in Table 3. The resulting system diagram is shown in Fig. 6. As shown in Fig. 6 the soft layers made of protein, an internal biotic part of the organism, perform the work of the pressure absorption. Control is done by environmental conditions as the work is based on the presence of external pressure in the environment. This control is based on a positive feedback as the magnitude of absorbed pressure is enlarged.

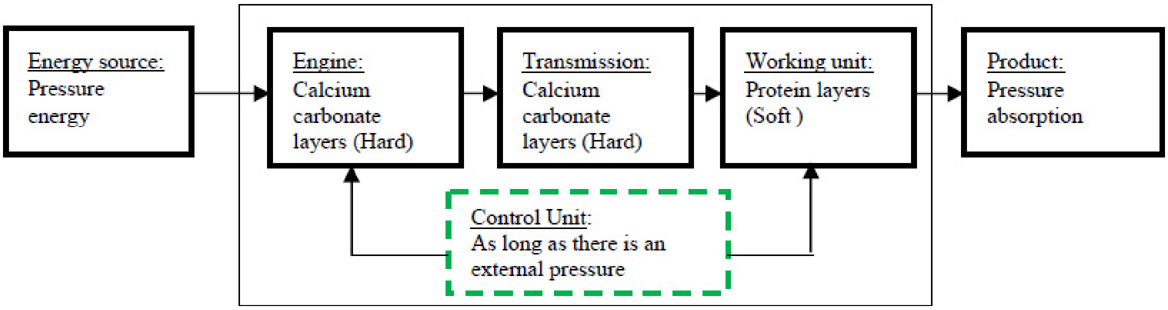

Fig. 6. Abalone shell pressure absorption mechanism- analysis by the law of system completeness

6.4. Non-Environmental working unit with a negative feedback: The Click-Beetle Jumping Mechanism

Description of Mechanism: The Click-Beetle has large longitudinal muscles in its body (see Fig. 7). These muscles are divided into two subunits by a hinge made of cuticular peg. The muscles contract to store elastic energy. When the peg slides and frees the hinge, the stored energy is abruptly released; then, the body is flexed and lifted from the ground within less than 1 ms. [14].

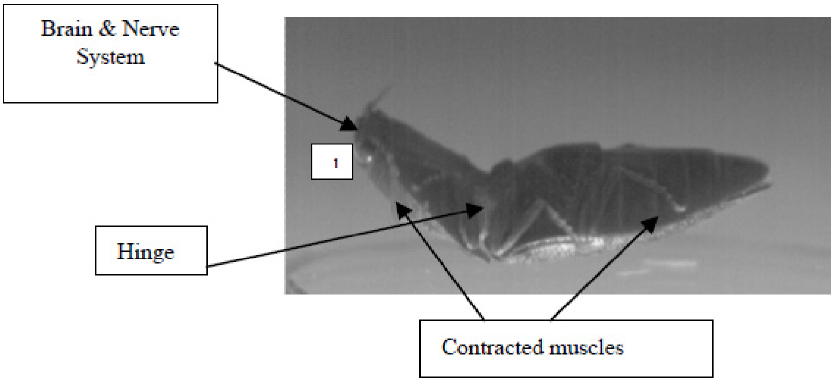

Fig 7: The Click-Beetle jumping mechanism
Photo 1 by Gal Ribak, reproduced with permission of the copyright owner.

The ten stages analysis procedure for this example is described in Table 3. The resulting system diagram is shown in Fig. 8. As shown in Fig. 8 the contracted muscles, internal biotic part of the organism, perform the function of engine, transmission and the working unit. The elastic energy is stored in the muscles and is used to lift the beetle body when the hinge is released. The control unit is part of the organism itself, the beetle's nerve system. This control is based on a negative feedback as the system is switched between two different positions: lifted body and non lifted body while the body position is changed in a certain range.

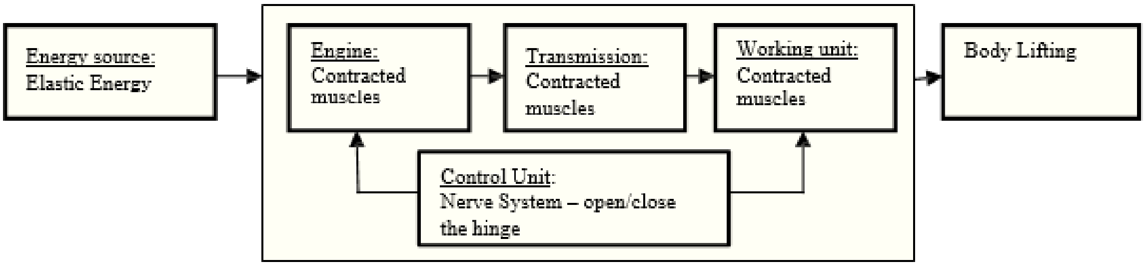

Fig. 8. The click-beetle jumping mechanism - analysis by the law of system completeness

Table 3: The ten stages analysis procedure – examples for each system type

	System type	Environmental working unit/Positive feedback	Environmental working unit /Negative feedback	Non-Environmental working unit/Positive feedback	Non-Environmental working unit /Negative feedback
		Lotus leaf	Gecko	Abalone Shell	Click- beetle
1	Identify the main function of the system.	Particles removal	Attach/ Detach gecko foot to surface	Pressure absorption	Body lifting
2	Which is the target object of this function?	Dirt particles (Mud, Dust etc.)	Gecko's foot	Shell	Beetle Body
3	Identify system parts: System, Super- system, Sub-system	Super system: Water droplets, Dirt Particles. System: Leaf Sub system: Epidermal protrusions	Super system: Surface System: Gecko Sub system: Setae (Hairs), Brain & Nerves	Super system: External objects that exert pressure System: Abalone Shell Sub system: Shell layers	Super system: Air System: Click beetle Sub system: Hinge, Brain & Nerve system, Muscles
4	Which Parts of the system are in physical touch with the target object?	Water droplets, Epidermal protrusions	Setae, surface	Shell layers	Muscles
5	Which part of the system performs the function?	Water droplets	Setae & Surface	Protein layers (Soft Layers)	Muscles
6	Which are the system parameters that are changed by the working unit?	Number of dirt particles	Number of setae in contact with surface	Magnitude of pressure absorbed	Positioning of body towards the ground
7	Which Source of energy is used to perform the function?	Adhesion forces (Chemical energy).	van der Waals Forces (Molecular Forces)	Pressure energy	Elastic energy of contracted muscles
8	Which part of the system converts this source of energy to work?	Epidermal protrusions	Setae	Calcium carbonate layers (Hard layers)	Contracted muscles
9	Which part of the system transfers this energy to the working unit?	Epidermal protrusions.	Setae	Calcium carbonate layers (Hard layers)	Contracted muscles
10	How does the system parameter change?	Reducing the number of dirt particles on leaf as long as there are particles and water.	The number of setae in contact with the surface is enlarged/reduced in certain rang.	Enlarges magnitude of pressure absorbed in case of external pressure.	Positioning of beetle's body towards the ground is changed in a certain range.

7. Discussion

Our analysis revealed four main types of biological systems (Table 2) that reflect different sustainable design principles:

1. Utilizing environmental elements as essential systems parts - We demonstrated that the working unit and the control unit may be provided by environmental elements. This design principle enhances sustainability as the energy and matter required for these essential parts are provided by the surrounding environment. It is less common to find technical systems whose essential system parts such as the working unit or the control unit are part of their surrounding environment
2. Utilizing environmental energy sources – We demonstrated that the interaction of system biotic elements with environmental elements enables utilizing environmental energy sources. The adhesion forces that enable the removal of the dirt particle from the lotus leaf are a result of the interaction between the droplets, the epidermal protrusions and the dirt particle. The van der Waals forces that enable the attachment and detachment mechanism of the gecko's feet are a result of the interaction between the feet and the surface. These interactions realize the potential of natural energy forces like physical, electrical and chemical forces and use them as clean and renewable free energy sources. In contrast, technical systems use energy sources like fuel, electricity or heat which are not necessarily clean or renewable.
3. Unification of system parts – Multi-Functional design is one of the prominent design principles in nature aiming to provide several functions by a singular component. When using the "Law of System Completeness" we demonstrated a tendency in some biological systems to combine several essential parts of the systems to the same component, mainly the engine and the transmission unit (Fig. 2), but sometimes the working unit as well (Fig. 8). Technical systems that demonstrate this design principle may enhance their level of sustainability as they save materials, although they might be more complex.

Comparing the four system types in Table 2 reveals that some systems exhibit more sustainable design principles and some exhibit less. For example, the first type, systems with an environmental working unit and a positive feedback, utilize environmental elements as essential system parts, exploit external renewable energy sources and might demonstrate some unification of system parts, as shown in the lotus effect cleaning mechanism (Fig. 2). On the other hand, systems with a non-environmental working unit and with a negative feedback control unit do not utilize environmental elements as essential system parts and do not utilize environmental energy sources, as shown in the click-beetle jumping mechanism (Fig. 8). This system type more resembles a technical system.

The above mentioned sustainable design principles are related to the Ideality of the system. According to the Law of Ideality, systems evolve in the direction of increasing their degree of Ideality. Environmental working unit with a positive feedback control unit demonstrate high level of ideality, as both the working unit and the control unit are absent as physical entities of the biological system while the required function is still performed at the right time and place. Using environmental energy sources reduce the negative aspects of the system, as the energy cost is reduced, and by that increase the ideality. Ideality of the system is also increased by transferring as many functions to the working parts. We demonstrated this aspect of ideality by the tendency of some biological systems to combine several essential parts of the system to the same component.

This study contributes both to TRIZ knowledge base and to biology and sustainability knowledge base: First, we demonstrated the applicability of the Law of System Completeness in the domain of biological systems, a new and uninvestigated domain in relation to this law as far as we know. We formulated the ten stages analysis procedure helping to reveal system parts according to the Law of System Completeness (Table 1). The TRIZ knowledge base was enriched by biological insights, like the two types of negative and positive control units. These types of control units are common in biological systems and contributed to a more specific definition of control unit types that is relevant also to technical systems. We defined the positive feedback control as an external control unit when the control is done by environmental conditions. The idea of an external control unit has already been demonstrated by Berdonosov [8] who offered a new scheme of the Law of System Completeness by adding an external control unit. The negative feedback control unit is an internal control unit and is more coordinated with the classic scheme of the law of system completeness. This type of control unit appears when there is a need to “switch” between different system conditions in order to keep the desired system parameter stable in a certain range.

On the other hand, we used a TRIZ tool to gain better understanding of the sustainable aspects of biological systems. Russo et al. [4] claimed that TRIZ tools provide guidelines to increase product sustainability and a better usage of resources. Indeed, the analysis of biological systems according to the Law of System Completeness provided us with sustainable guidelines derived from the definition of a sustainable structures typology (Table 2). These guidelines may be later integrated with eco-design tools. For example, instead of isolating the technical system by using covers and coating, the designer should find ways to integrate it with the environment for a better sustainable performance.

The analysis provides an operational language that eases the transformation of design principles from biology to engineering, as required during the biomimetic design process. The analysis enabled us to abstract biological system structures in a comprehensible way for engineers. Further research should focus on comparing analysis results of different "experts" using the same 10 stages procedure (Table 1). Differences in analysis results may shed light on the complexity of the biological mechanism, mainly in cases of stepwise processes or concurrent mechanisms. For example, when analyzing the lotus dirt removal mechanism one may focus on the first step of attaching the dirt particle to the water droplet (Fig.2) while another may focus on the second step of the water droplet rolling of the leaf. Comparing their results may give better understanding of the full stepwise process.

This study is a first stage in our general effort to abstract sustainable design principles towards a formation of a new biomimetic design method. We aim to elaborate our knowledge base using other TRIZ tools like substance-field analysis.

Biological systems can be further used as guidelines to drive innovative designs of sustainable technical systems, as biological systems demonstrate high levels of ideality, and ideal systems, in a way, are more sustainable systems.

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