INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

VISUAL REPRESENTATIONS AS A BRIDGE FOR ENGINEERS AND BIOLOGISTS IN BIO-INSPIRED DESIGN COLLABORATIONS

Hashemi Farzaneh, Helena; Helms, Katharina; Lindemann, Udo
Technical University Munich, Germany

Abstract

In technical product development, engineers address technical problems by developing innovative solutions. An approach to develop ideas with a high potential for technical innovation is bio-inspired design or biomimetics. It implies the transfer of information and knowledge from biology to develop a technical solution. This transfer is a challenge, since engineers do not necessarily have sufficient knowledge in biology. On the other hand, biologists do not necessarily have knowledge in technical product development. Direct collaboration between engineers and biologists can be a solution, but due to the different educational background, misunderstandings can be a barrier. In this work, we develop common visual representations for biologists and engineers to overcome this barrier, based on the analysis of representations in both disciplines. We evaluate the guidelines for modeling technical and biological systems with these common visual representations in tests with engineers and biologists.

Keywords: Bio-inspired design and biomimetics, Collaborative design, Visualisation

Contact:
Helena Hashemi Farzaneh
Technical University Munich
Institute of Product Development
Germany
hashemi@pe.mw.tum.de

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

Nature offers innumerous biological solutions tested by evolution (VDI 2012) – exploring this vast solution space can provide high-potential solutions for technical product development. Biomimetic or bio-inspired design approaches have been developed (e.g. by (Hill 1997, Gramann 2004, Chakrabarti et al. 2005, Vattam et al. 2011)) to support the search for biological solutions and their transfer to the technical domain. However, engineers can lack biological knowledge necessary to derive solution principles from biological systems. Biologists, on the other hand, do not necessarily possess the technical knowledge needed to develop technical solutions and products. The collaboration of engineers and biologists can be beneficial to successfully develop technical products from a biological inspiration. Still, even in a multi-disciplinary collaboration, the understanding of the other discipline is a challenge due to the different educational background and the different use of terminology (Helten et al. 2011). Visual representations are a possibility to overcome this barrier.

In this work, we analyze and compare visual representations used in technical product development and biology to discover communication paths for supporting collaboration. Common features are identified in the examined visual representations (section 3). Based on the features, common visual representations and guidelines for modeling technical and biological systems with these representations are developed (section 4). They are evaluated with mechanical engineers and biologists who have different degrees of expertise (section 5).

2 BACKGROUND

In this section, we give an overview on visual representations and their use in technical product development and biology. Then, we introduce different approaches to knowledge and information transfer in bio-inspired design.

2.1 Visual representations

Representations or models represent an original object (Stachowiak 1973). They differ from the original as they possess a reduction feature, i.e. they do not represent all of the original's attributes. They are aimed at a specific purpose, i.e. have a pragmatic feature (Stachowiak 1973). In technical product development, different product models are used throughout the product development process (Ponn and Lindemann 2011, Vajna et al. 2009, Kohn et al. 2012). From the development of a requirements list in the early phases of the product development process to a CAD model and technical drawings in the later stages, product models fulfill different purposes (pragmatic feature) and have different degrees of abstraction (reduction feature) (Kohn et al. 2012). In biology, (Haefner 2005) differentiates three possible purposes of models (pragmatic feature): Understanding, prediction and control. According to (Leonelli 2008) they imply a "rendering" of a biological phenomenon, i.e. possess a reduction feature.

With regards to the visual form of representations, (Kohn et al. 2012) analyze product development literature and conclude that authors differentiate between analytic, graphical, tabular/ matrice and textual representations. In previous work, we identified graphical representations completed by textual annotations and analytic representations in two standard introductory biology books (Hashemi Farzaneh et al. 2015).

Why are graphic or visual representations interesting for biomimetic collaboration?

According to (Spence 2007), visualizing implies the formation of a mental model or a mental image of an object. (Ware 2012) states that so-called sensory symbols in a visualization can be understood without previous training and are valid in different cultures. To conclude, visual representations can support understanding and knowledge transfer in collaborations of engineers and biologists. If visual representations are designed adequately, engineers and biologists can both understand them despite their different training.

2.2 Knowledge and information transfer in bio-inspired design

In bio-inspired design, representations are used to transfer information about a biological system to the technical domain for solving a technical problem or task. Vice versa, representations can be used for transferring information about a technical system to the biological domain. Knowledge can be

regarded as cross-linked information (Probst et al. 2010) possessed by persons – therefore the transfer of information is a prerequisite for the exchange of knowledge between persons.
Several approaches match biological and technical information via functions, e.g. (Hill 1997, Gramann 2004, Löffler 2009, 'The Biomimicry 3.8 Institute' 2014, Lenau et al. 2011) enable accessing biological systems via the formulation of a technical problem or task as a function. The function is formulated as a verb (e.g. "clean") or a verb and an object (e.g. "clean surfaces"). Using the function, a biological system can be matched which is explained by sketches/ photos and a description of the solution principle. This approach is enhanced by (Vattam et al. 2011) who additionally use behavior and structure for information transfer. (Chakrabarti et al. 2005) developed the SAPPhIRE model, which allows for representing and matching a technical and a biological system with seven constructs building on function, behavior and structure. The described approaches are used to build collections of biological systems and store them – for example in electronic databases (Löffler 2009, 'The Biomimicry 3.8 Institute' 2014, Vattam et al. 2011, Chakrabarti et al. 2005) or on "inspiration cards"(Lenau et al. 2011). This information storage can be used by engineers searching for a solution to their technical problem. However, databases only contain information about a limited number of biological systems which have been added previously. The described approaches are not used by both engineers and biologists to represent and communicate up-to-date information about technical or biological systems from their current research.
To support communication between engineers and biologists, (Jordan 2008) proposes a person familiar with both technical product development and biology to act as a mediator in a direct collaboration. (Helten et al. 2011) urge that biologists and engineers have to discuss their different use of terminology and differing "mind-sets" to improve communication.
As explained in section 2.1, representations, in particular visual representations, can be a support to overcome these challenges. In section 3, we develop visual representations for supporting the communication between engineers and biologists.

3 VISUAL REPRESENTATIONS IN TECHNICAL PRODUCT DEVELOPMENT AND BIOLOGY

To develop visual representations for information transfer, representations used in technical product development and biology are analyzed and compared.
In previous work, representations containing relevant information for bio-inspired design from two introductory biological books used world-wide in the first year of biology university courses have been analyzed. The analysis showed that each representation possesses at least one of the features shown in **Table 1** (Hashemi Farzaneh et al. 2015).

Table 1. Features identified in representations from biology (revised description) (Hashemi Farzaneh et al. 2015)

Feature	Definition
morphological	representation of the morphology of a biological system, i.e. the shape and/ or structural relations of its elements
relational	representation of cause-and-effect relations between several biological systems or system elements
change	representation of the change of a biological system or system elements
data	representation of quantitative or qualitative data acquired about a biological system or its elements
mathematic	a mathematic representation of a biological system or its elements
comparative	representation of a comparison between several variations of biological systems or its elements

Accordingly, representations from technical product development containing relevant information for bio-inspired design (identified in (Hashemi Farzaneh et al. 2015)) are analyzed with regards to these six features. The result is shown in **Table 2**: All features identified in biological models are also present in models from technical product development. We therefore assume that both engineers and biologists are familiar with the features and can represent information about a technical or biological model using these features.

Table 2. Analysis of representations from technical product development

Representation	**Identified feature(s)**
Requirements list	data feature
List of functions, functional model	change feature / relational feature
Sketches of working principles	morphological feature / mathematic feature
morphological box	comparative feature, morphological feature
TRIZ functional model	morphological feature, relational feature
Relational system model	morphological feature, relational feature

Representations from technical product development described by (Ponn and Lindemann 2011, Pahl et al. 2007, Adunka 2007)

4 DEVELOPMENT OF GUIDELINES FOR VISUAL REPRESENTATIONS OF TECHNICAL AND BIOLOGICAL INFORMATION

Based on the six features described in section 3, we develop guidelines for representing technical and biological information. In order to minimize the effort for the engineer or biologists using the guidelines the six features are integrated into three representations: *system description*, *system behavior* and *system properties*. Moreover, parts of one representation can be reused for another representation; this is explained in the following.

The morphological feature represents the shape of a system and additionally the structural relations between its elements. The shape of a system can be explained in a sketch or photo as shown in the example of a *system description* in **Figure 1**.

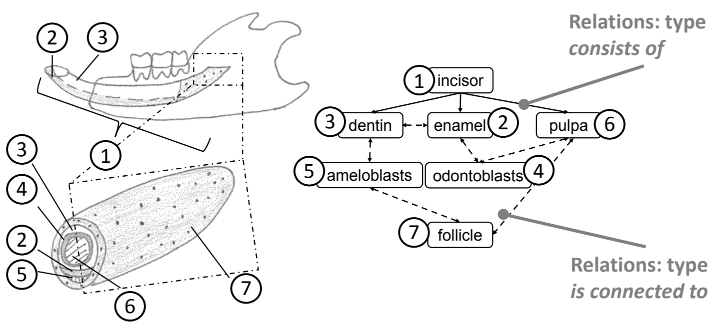

Figure 1. System description (morphological feature) of the system rodent tooth (Roche Lexikon Medizin 2003, Kuang-Hsien Hu et al. 2014)

The specific elements of the systems are labeled. Then, their structural relations are depicted as shown in **Figure** 1. There are two types of relations: *consists of* and *is connected to*. The example in **Figure 1** is a representation of the biological system *rodent tooth*. Rodent teeth consist of a comparably soft material, dentin, and a hard material, enamel. Together with the pulpa, dentin and enamel form the incisor. The follicle embeds the pulpa. Ameloblasts and odontoblasts are connected to dentin and enamel.

The change and relational feature are integrated in a second representation, the *system behavior*. It consists of system elements connected by two types of relations. The relation *impacts on* represents the relational feature; the relation *changes to* represents the change feature. The biologist or engineer is asked to follow the three steps shown in **Figure 2**. First, external elements and their relations of the type *impacts on* with the system have to be depicted. In case of the rodent tooth, “food” is a relevant external element. As shown in the figure, the relations of the type *impacts on* are labeled.

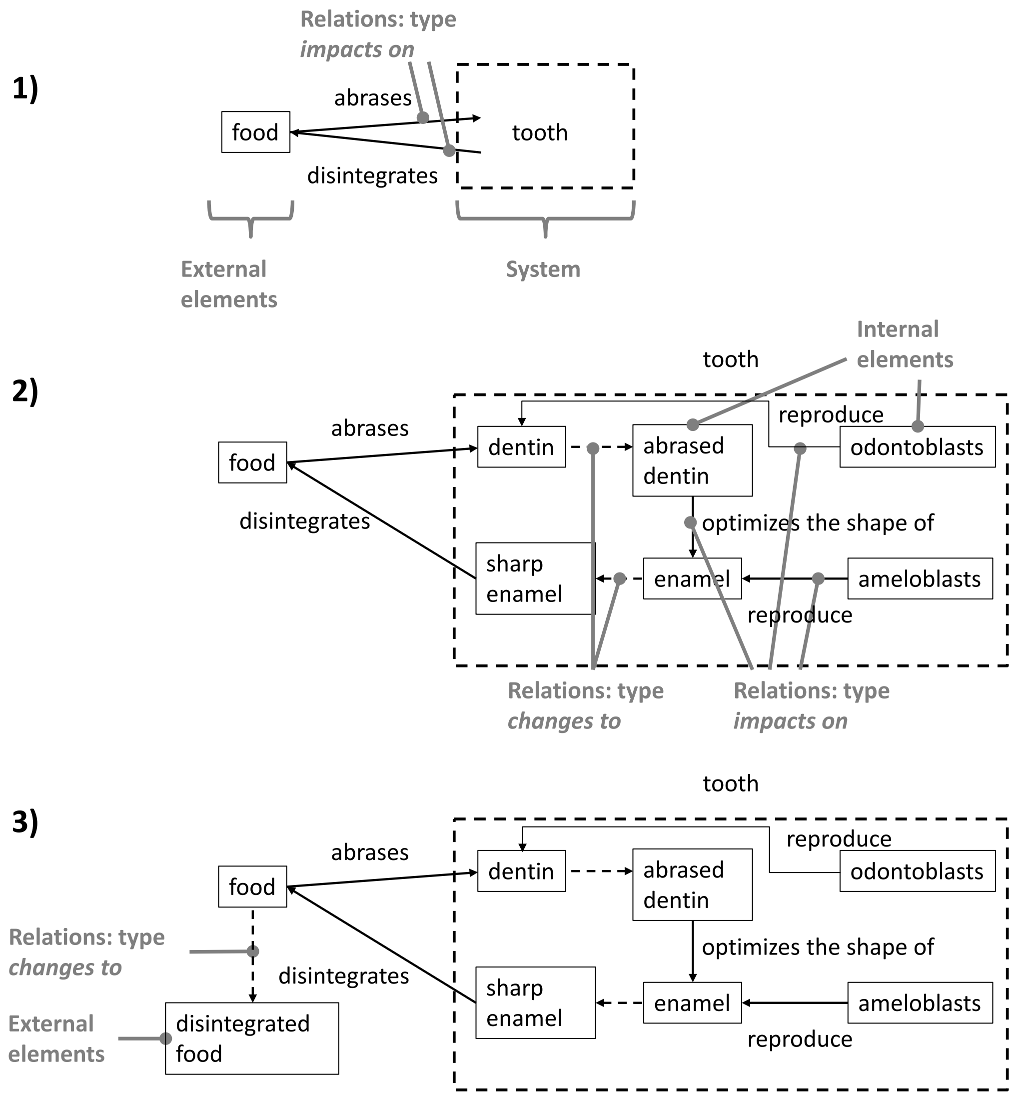

Figure 2.Three steps to represent the system behavior of a "rodent tooth" (Roche Lexikon Medizin 2003, Kuang-Hsien Hu et al. 2014)

Second, the internal elements from the system description (see **Figure 1**) can be included. They are related by both types of relations. As the example in **Figure 2** shows, the *external element* "food" "abrases" the *internal element* "dentin", which consequently *changes to* "abrased dentin". As the dentin layer is abrased, it "optimizes the shape" of the "enamel" layer. The "enamel" consequently *changes to* "sharp enamel" which disintegrates the food. "Odontoblasts" "reproduce" "dentin", "ameloblasts" "reproduce" "enamel". As can be seen, the relations of the type *changes to* are not labeled.

Third, the relations of the type *changes to* are added to the external elements. In case of the example, "food" *changes to* "disintegrated food".

The representation for *system properties* is based on the *system behavior* and adds data and mathematical feature. This is shown for the *rodent tooth* example. It includes data of the system elements, e.g. the composition of enamel and dentin, and of the relations, e.g. ameloblasts "continuously" reproduce enamel. Relations can additionally be described by mathematic equations, e.g. the volume of reproduced enamel can be calculated by multiplying time with a factor ("$V_{enamel} = T \bullet x$").

The comparative feature does not have to be described by a different representation – it is a comparison of differing systems and can therefore be shown by contrasting one of the representations *system description, system behavior* and *system properties* of the differing systems.

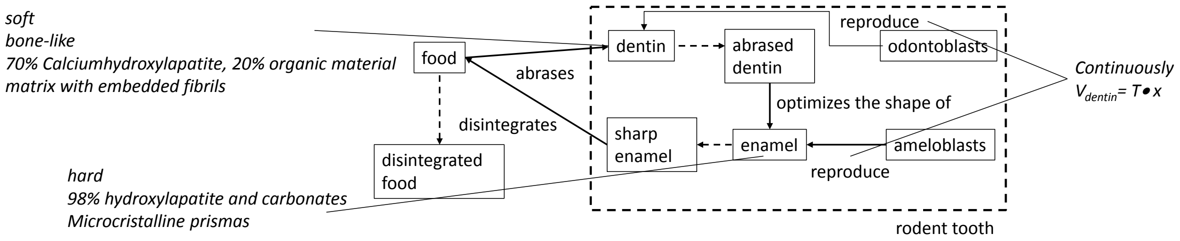

Figure 3. System properties of a "rodent tooth" [21, 22]

5 EVALUATION OF THE GUIDELINES: USABILITY BY BIOLOGISTS AND ENGINEERS

For evaluation, firstly, the usability of the guidelines has to be tested: Can biologists and engineers represent a biological or technical system using the guidelines?
In a second step, it has to be evaluated whether the understanding of the biological or technical system is facilitated by the visual representations for a non-expert. This is not part of this work and has to be done in future work. In this section, we describe the research methodology, followed by the results regarding the usability of the guidelines for the system description, system behavior and system properties.

5.1 Research methodology

The guidelines were tested with seven participants: Three doctoral candidates (two graduated biologists: B1, B2, one graduated engineer: E2) and four undergraduate students (two students of biology: b3, b4, two students of mechanical engineering: e2, e3). The participants were given guidelines describing the steps for representing a technical/ biological system as explained in section 4. The guidelines also included the simple example of the system "tree" interacting with plant louses. The participants received paper and pens for representing a system in approximately 60 minutes for which they rated themselves expert. The engineers represented a rapid-prototyping machine (E1), a logotherapy device (e2) and a coffee machine (e3). The biologists represented a habitat model of the grey goose (B1), a deer (B2), the salicylic acid-system of a plant (b3) and barley (b4). The developed visual representations were analyzed by the authors with regards to quantified measures explained in section 5.2.

5.2 Results

In the following, the results for the development of the *system description*, the *system behavior* and the *system properties* are shown.

5.2.1 System description

The developed system descriptions were analyzed using the measures shown in **Table 3**. To start with, we regarded whether the system description included a sketch showing the labeled elements of the system. This was the case for three of the seven participants. The participants were asked to label the five most important elements of the system. As can be seen in **Table 3**, five participants did this and one participant labelled seven instead of five elements. The participant b3 did not develop a system description. The number of relations varied, but the majority of the participants used both relation types.
To conclude, some of the participants had difficulties in using both types of relations demanded by the guidelines. The usability of the guidelines could be improved by enabling the reuse of existing figures (sketches or photos) instead of asking for a new sketch.

Table 3. Results of the evaluation of the guidelines regarding the system description

Measure	**E1**	**e2**	**e3**	**B1**	**B2**	**b3**	**b4**
Is there a sketch of the system? (y=yes, n=no)	n	y	y	y	n	n	n
How many elements are used?	5	7	5	5	5	0	5
How many relations of the type "consists of" are used?	0	5	1	2	0	0	4
How many relations of the type "is connected to" are used?	3	1	3	3	6	0	3

Mec. engineers: doc.cand. (E1), students (e2, e3), Biologists: doc.cand. (B1, B2), students (b3, b4)

5.2.2 System behavior

Table 4 shows the results of the evaluation of the guidelines regarding the system behavior. As the participants were asked to follow the three steps illustrated in **Figure 2**, some of them drew two or three representations.

In the first step, we analyzed the number of external elements and the number of relations established to the system. The participants were asked to list one to five external elements and establish relations of the type "impacts on" to their system. As can be seen in **Table 4**, the majority of the participants listed up to five external elements and represented up to five relations to the system. Again, biologist b3 was an exception. This participant did not develop a system description, had difficulties in defining the system boundaries and therefore did not define external elements. Furthermore, it has to be observed that some of the participants changed the external elements and their relations if they drew a separate representation for the second step. In the second step, most participants reused the internal elements from the system description, sometimes adding new elements. They also established a number of relations of the type "impacts" on, but did not always label them. In comparison, they established few or no internal and external relations of the type "changes to" (step 2 and 3). This can be explained by the nature of the represented systems, but it can also be due to a confusion regarding the different types of relations. This assumption is supported by the fact that the two students of biology (b3, b4) did not unambiguously mark the different types of relations.

In conclusion, the system behavior could be represented by the majority of the participants. An important learning for a software implementation of the guidelines is that, changes have to be made during the representation process. In addition, the differences between the types of relation "impacts on" and "changes to" have to be clarified for the user. The labeling of the relation of the type "impacts on" must be obligatory.

Table 4. Results of the evaluation of the guidelines regarding the system behavior

Measure	**E1**	**e2**	**e3**	**B1**	**B2**	**b3**	**b4**
How many external elements are used? (step 1)	4	2	2	3	5	0	2
How many relations of the type "impacts on" are established between external and internal elements? (step 1)	4	3	5	3	5	0	2
How many internal elements from the system description are re-used? (step 2)	5	5	5	5	4	0	5
What is the total number of internal elements – not considering the "changed" elements? (step 2)	5	5	5	7	4	6	12
How many relations of the type "impacts on" are used between internal elements? (step 2)	6	6	4	8	6	14	11
How many relations of the type "changes to" are used for internal elements? (step 2)	0	1	2	0	0	6	5
How many relations of the type "changes to" are used for external elements? (step 3)	0	1	1	0	1	0	0

Mec. engineers: doc.cand. (E1), students (e2, e3), Biologists: doc.cand. (B1, B2), students (b3, b4)

5.2.3 System properties

To represent the system properties, the participants were asked to assign at least one property to each element and to each relation. As can be seen in **Table 5**, none of the participants assigned properties to all elements and relations. However, all participants assigned more than six properties in total to elements. Less than half of the participants assigned properties to the relations. With regards to a mathematic description, it was established by four of the participants. Except for one participant, the mathematic descriptions were not equations, but approximated graphs.
To conclude, the assignment of properties and mathematic descriptions to relations has to be explained and facilitated for the user – for example the addition of approximated graphs can be enabled.

Table 5. Results of the evaluation of the guidelines regarding the system properties

Measure	**E1**	**e2**	**e3**	**B1**	**B2**	**b3**	**b4**
How many elements are annotated with properties?	3	5	5	4	9	6	11
How many properties are assigned to elements?	6	6	19	8	22	21	27
How many relations are annotated with properties?	3	4	0	0	0	0	4
How many properties are assigned to relations?	3	7	0	0	0	0	6
How many mathematic descriptions are assigned to relations?	1*	1**	0	1**	1**	0	0

Mec. engineers: doc.cand. (E1), students (e2, e3), Biologists: doc.cand. (B1, B2), students (b3, b4)
*equation, **approximated graph

6 CONCLUSION, DISCUSSION AND OUTLOOK

In this work, we developed common visual representations and guidelines to model biological and technical systems. They are based on common features identified in representations used in both disciplines. Guidelines enable engineers and biologists to represent a system for which they are experts. Using a common representation aims at facilitating information and knowledge transfer between engineers and biologists in bio-inspired design projects. We evaluated the usability of the visual representations and guidelines with seven participants from both disciplines. The results provided possibilities for improvement, in particular for the implementation of the visual representations in a software-based communication platform.
This work has several limitations, in particular with regards to the evaluation of the guidelines: The expertise of the participants regarding the system they represented varied. In case of the students, they possibly did not possess sufficient knowledge. This could also explain the difficulties of the biology students. In addition, the systems the participants represented do not cover the entire field of biology or technical product development.
In future work, the usability of the guidelines for representing technical and biological systems can be tested further. Moreover, the facilitation of information and knowledge transfer in a collaboration of engineers and biologists has to be evaluated. As a goal, the visual representations and guidelines will be implemented in a communication platform, which supports searching for cooperation partners for bio-inspired design and establishing a first understanding between engineers and biologists.

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