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EMBODIMENT DESIGN BASED ON BASIC SCHEMATA

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1. Introduction

Computer tool SoPHY (**S**ynthesis of **PHY**sical laws; available at http://www.lecad.fs.uni-lj.si/research/theory/phlaw_chains/software) was developed to support design engineers during conceptual design of technical systems. It is based on the chaining of physical laws and complementary basic schemata. The result of chaining is a chain; this represents an elementary product concept and describes the transformation of an input quantity to an output quantity (i.e. an abstract description of the mode of action).

A basic scheme is an abstract structure which is complementary to a physical law. Such an abstract structure has certain geometry, geometric position and relevant environment (represented by material and fundamental constants). It represents a structure capable of performing the transformation of quantities according to a physical law to which it is complementary. Each physical law has only one basic scheme. The consequences of this are at least twofold: (1) basic schemata provide chances for various embodiments [Rihtaršič et al. 2009], which in turn lead to potentially inventive solutions, and (2) the set of building blocks is small (thus enabling easy database maintenance).

According to [Dorst 2008] the lack of testing of design methods (and tools) is one of the five major areas of concern regarding the current situation in design research. Therefore, the authors started with series of experiments to shed light on usefulness of the computer tool. The first experiment showed that there is statistical significance in variety of design concepts generated by the CLASSIC group (using functional structure and morphological matrix) and the SOPHY group (using a chain of physical laws and complementary basic schemata) [Žavbi et al. 2011]. During discussion within the ICED2011 Conference, a commentary regarding the CLASSIC group was given: (student) industrial designers might generate different solutions and should also be taken into consideration.

The authors therefore designed a partial experiment to obtain solutions generated by (student) industrial designers and compare them with the solutions generated by the SOPHY group during the first experiment.

2. Methodology

Embodiment design is performed by a design engineer, who uses synthesized chain(s) of physical laws and basic schemata (i.e. results of automatic chaining with SoPHY (Figure 1)) as starting points. Chains of basic schemata are abstract, but here we took into consideration Hubka, who stated that a higher abstraction offers greater possibilities for variation (although at the expense of more effort by the designer) [Hubka and Eder 2002]. It was assumed that, although abstract, basic schemata offer guidance (a kind of creative stimuli) for alternative embodiments of synthesized chains, and they also lessen the effort required from the design engineer due to a more focused approach (i.e. embodiment of automatically synthesized chains).

This assumption was articulated as the following **research hypothesis**: The use of a chain of physical laws and basic schemata offers greater possibilities for variation (i.e. embodiment of different solutions) than use of regular methods used by (student) industrial designers. Consequently, the **null hypothesis** is stated as follows: The use of a chain of physical laws and basic schemata offers no greater possibilities for variation (i.e. embodiment of different solutions) than use of regular methods used by (student) industrial designers.

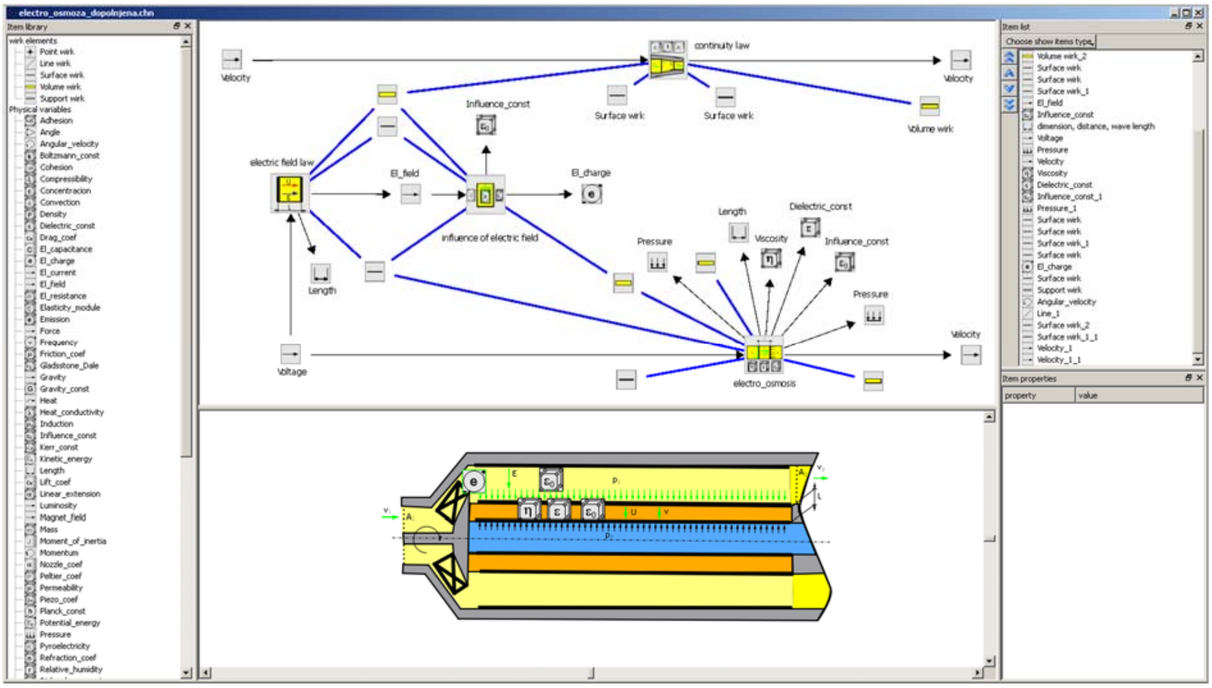

Figure 1. Structural synthesis module of the SoPHY tool [Rihtaršič et al. 2009]

2.1 Subjects

The second year students of industrial design were asked to participate in an experiment; 21 out of 23 accepted the invitation. They formed the INDES group. All the students took the same courses during the first year of their studies; product conceptualisation was among them.
The other group (i.e. experimental group; SOPHY group) consisted of students of mechanical engineering attending the Design methodology course in the third year of their studies. They also took the same courses during the first two years, predominantly related to basic and engineering sciences (e.g. Mathematics, Physics, Chemistry, Statics, Material Strength, Dynamics, Fluid Dynamics, Thermodynamics, Materials Science) [Žavbi et al. 2011].

2.2 Evaluation metrics

According to [Shah et al. 2000, 2003], there are two fundamental measures to evaluate the usefulness of a conceptual design method: (i) effectiveness of expanding the design space and (ii) thoroughness of exploring the design space. They proposed quantity, quality, novelty and variety as specific measures; to begin with, quantity and variety were adopted in our experiment. It is argued that a method/tool is worth using if it helps a design engineer with any of the above mentioned measures [Shah et al. 2003].
Variety is a measure of explored design space; the generation of similar ideas indicates a low level of variety and consequently a lower probability of finding better ideas in the solution space [Shah et al. 2003]. Difference in embodiment was sufficient for the concept design to be regarded as different. If two concept designs differ only in detail then they were regarded as equal. E.g. concept designs illustrated in Figures 5 and 6 were regarded as different, while the concept designs in Figure 7 were regarded as equal.

2.3 Design task

The design task was kept simple in order to focus on the evaluation of variety. Apart from the basic function, no additional requirements were given. The design task involved the conceptualization of a technical system for emptying a tube (e.g. of toothpaste, of shoe cream, of paint).

Since the students were asked to use two different methods, the text for the both groups was slightly different. The text for the group INDES was as follows:

- Develop concepts for a technical system to be used for emptying a tube (e.g. of toothpaste, of shoe cream, of paint). The concepts should be presented by a sketch (mandatory) and text (optionally).

The text for the group SOPHY was as follows (equations describing the physical laws in the chains were also supplied within the text, while in this paper they are omitted for brevity):

- Based on the chain of physical laws and basic schemata (Figures 2-4 were also a part of the design task for the SOPHY group; [Žavbi et al. 2011]), an embodiment of a technical system for emptying a tube (e.g. of toothpaste, of shoe cream, of paint) has to be developed.

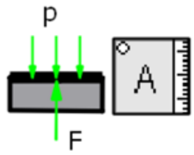

Figure 2. A chain of physical laws (1 physical law) and complementary basic schemata (1 basic schema)

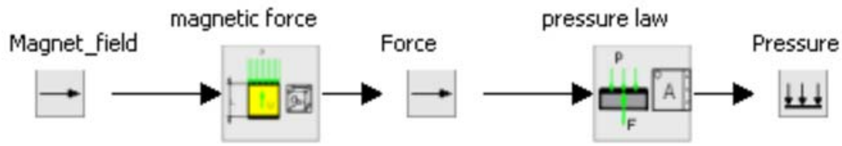

Figure 3. A chain of physical laws (2 physical laws) and complementary basic schemata (2 basic schemata)

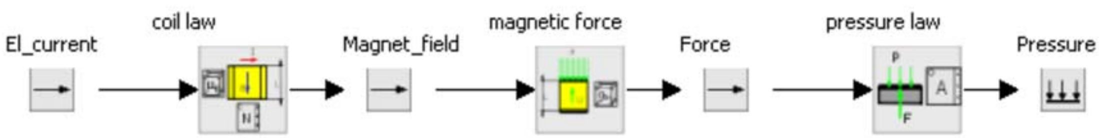

Figure 4. A chain of physical laws (3 physical laws) and complementary basic schemata (3 basic schemata)

2.4 Procedure

In this second experiment experimental results of the SOPHY group (i.e. experimental group) from our first experiment (involving the conceptualization of a technical system for emptying a tube (e.g. of toothpaste, of shoe cream, of paint)) were used [Žavbi et al. 2011]. The procedure with the INDES group was performed as follows: At the beginning of the 3rd semester the students of industrial design at the same university (as the students of mechanical engineering) were given the design task as described in the subsection 2.3. The time allocated was 30 minutes according to [Howard et al. 2011]. These results were collected and classified. The first author evaluated the results of both groups regarding the quantity and variety of solutions.

3. Generated concept designs and analysis of the results

The 21 students from the INDES group generated 74 solutions (16 of which were different), while the 23 students from the SOPHY group generated 58 solutions (35 of which were different [Žavbi et al. 2011]). Examples of these solutions are presented in Figures 5-11 below.

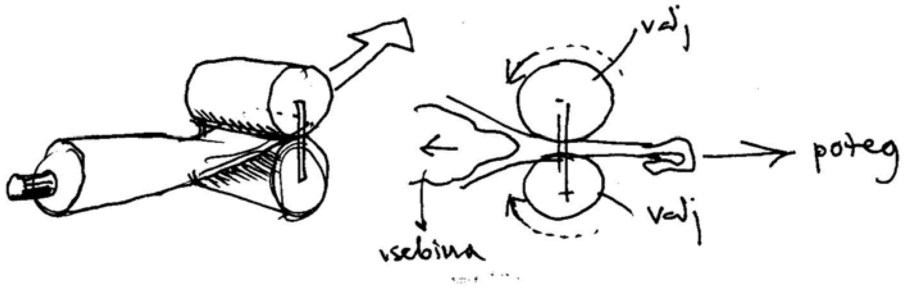

Figure 5. Two-roller squeezer (INDES group)

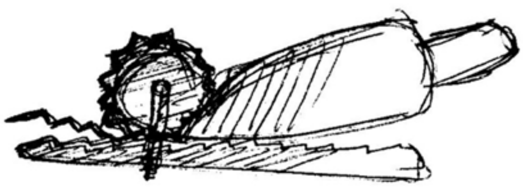

Figure 6. Rack and pinion squeezer (INDES group)

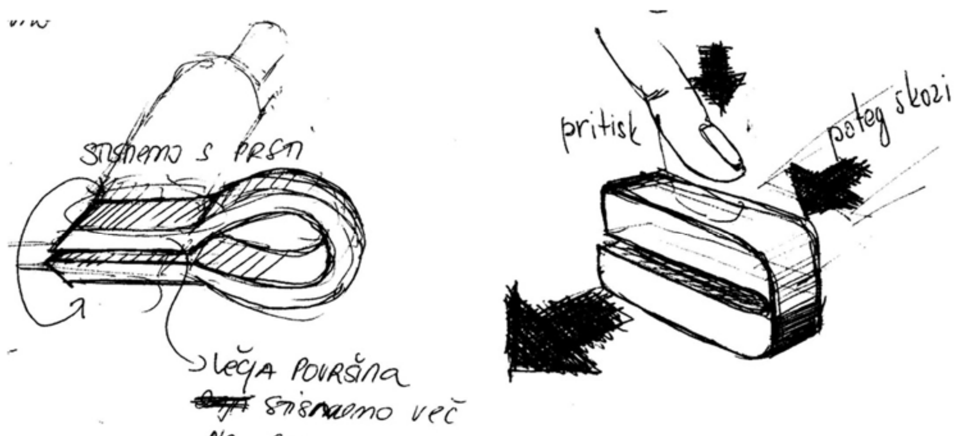

Figure 7. Clip squeezers (INDES group)

The type of concept design depicted in Figure 5 was generated by 17 students out of 21 of the INDES group, while the type of concept design depicted in Figure 6 was generated only once; there were 6 design concepts, which were generated only once.

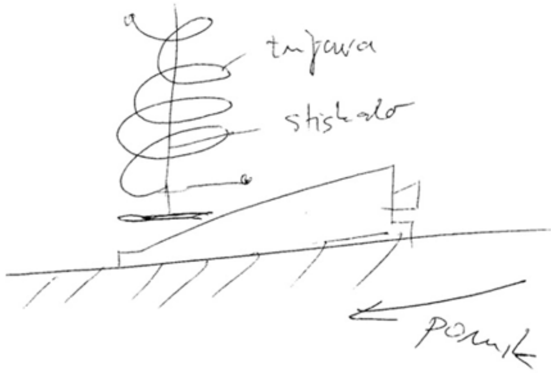

Figure 8. Voice coil actuated plate squeezer (SOPHY group)

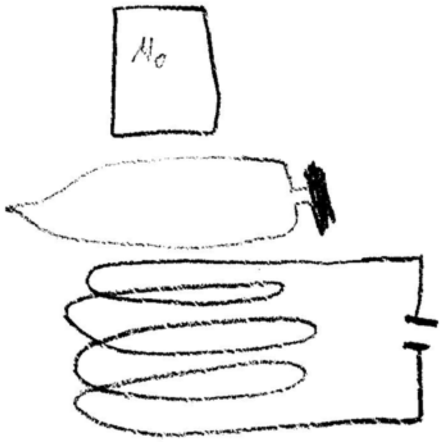

Figure 9. Voice coil squeezer (SOPHY group)

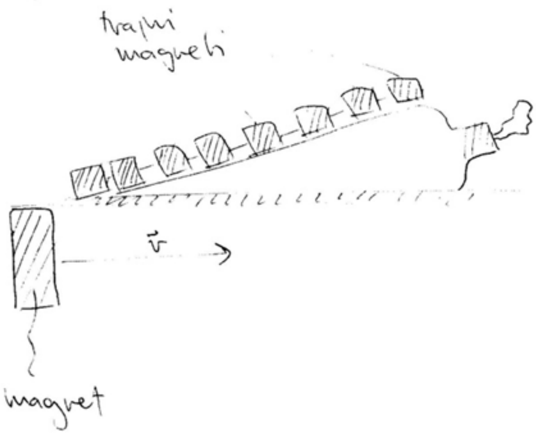

Figure 10. Permanent magnet squeezer (SOPHY group)

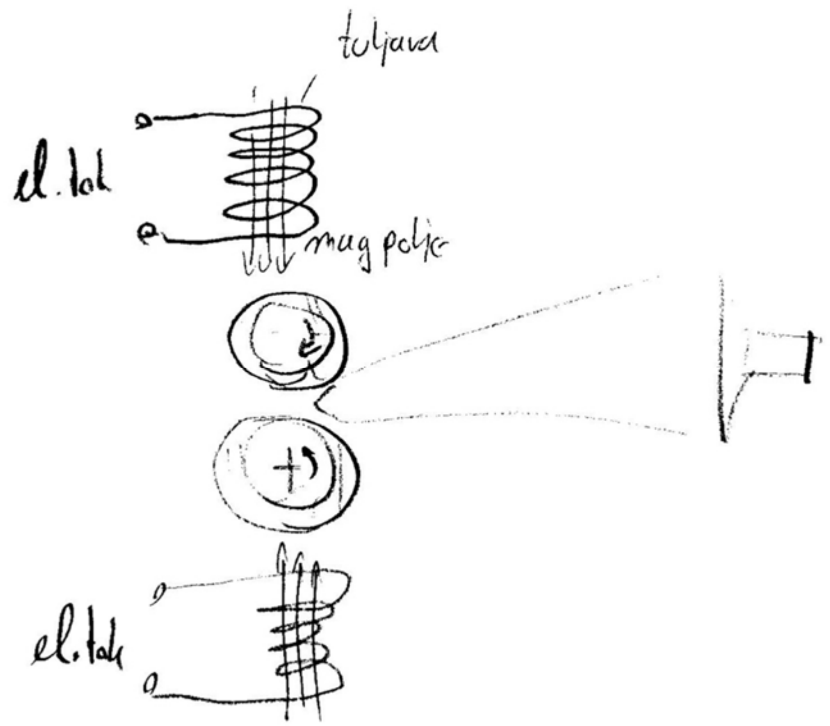

Figure 11. Voice coil actuated roller squeezer (SOPHY group)

8 students out of 23 of the SOPHY group generated the type of concept design depicted in Figure 8, while the type of concept design depicted in Figure 10 was generated only once. Frequency of design concept replication for both groups is illustrated in Figures 12 and 13.

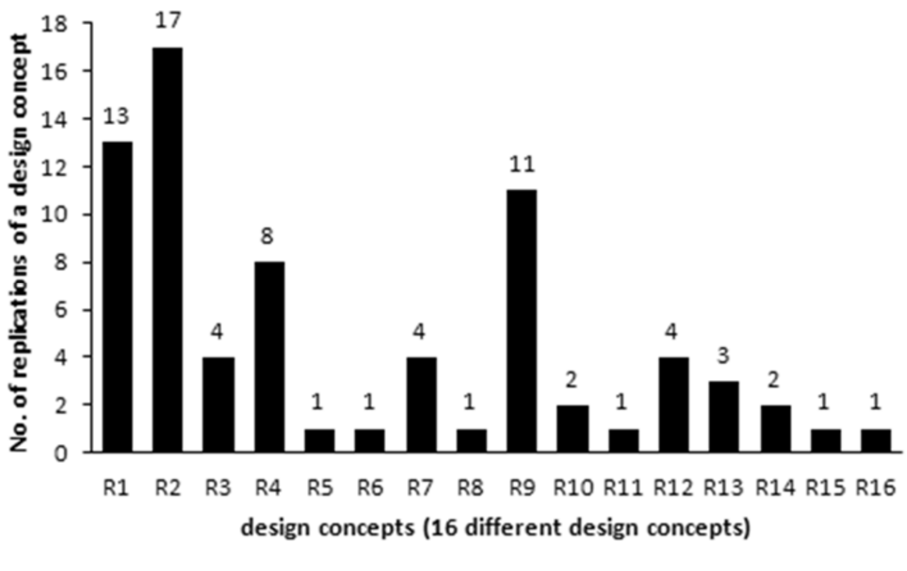

Figure 12. Histogram of generated design concepts (INDES group)

Table 1 presents the results of the INDES and SOPHY groups. The numbers of obtained solutions show that the students who used chains of physical laws and complementary basic schemata (i.e. SOPHY group) managed to produce a greater number of different solutions. E.g. approx. 22% of design concepts generated by the INDES group were different, while approx. 59% of design concepts generated by the SOPHY group were different.

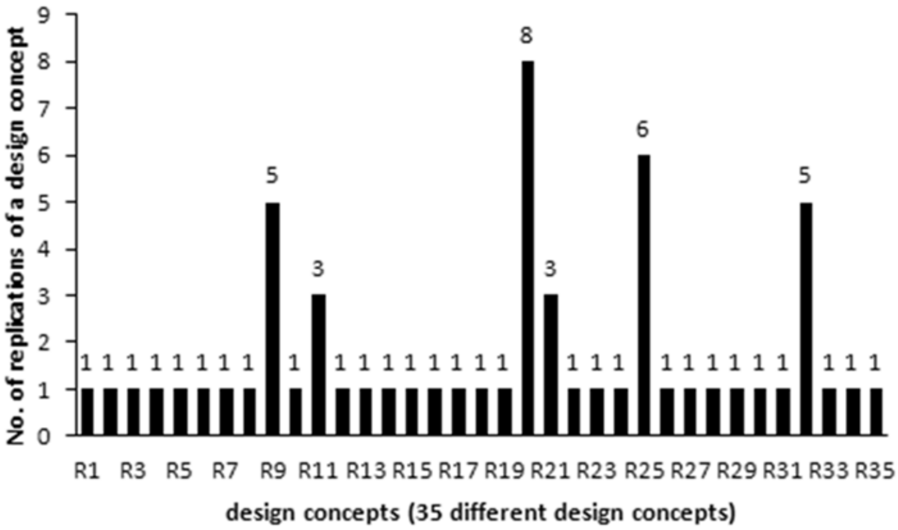

Figure 13. Histogram of generated design concepts (SOPHY group)

In order to avoid this result being accidental, statistical tools were implemented for data analysis. The calculation of chi-square (χ^2) was done in order to validate the statistical significance of the results. χ^2 is a tool used when the goal is to compare two independent samples and determine the relevance of their differences [Petz 2007].

The obtained χ^2 at 1 degree of freedom and probability 5% is 3.841 [Petz 2007]. As the calculated value of χ^2 (i.e. χ^2 = 2,7) is lower than this, the null hypothesis cannot be rejected (the research hypothesis cannot be confirmed).

Table 1. Results for the design task

Group	No. of students	No. of solutions	No. of different solutions
INDES	21	74	16
SOPHY	23	59	35

4. Discussion

Surprisingly, the result (acceptance of the null hypothesis) is different than the result obtained by the first experiment where the control group consisted of (student) design engineers [Žavbi et al. 2011].

Finke intuitively predicted that subjects would be more creative when building blocks are specified than when they are selected freely by the subjects themselves; his experiments confirmed his intuition [Finke et al. 1992].

The authors believe that the reason for the statistical insignificance of the difference of the results (i.e. variety of generated design concepts) of the INDES and SOPHY group is focus of the students of the INDES group on the embodiment of mechanical physical principles. This means that the students of industrial design embodied a limited set of physical principles they were familiar with (i.e. mechanical ones) and that this limited set of physical principles acted as a constraint that enhanced the creative potential of the task (as predicted and confirmed by Finke for his experiments). It is the fact that studies of the industrial designers are focused on "idea with the product" and not "idea in the product" (as described by [Hansen and Andreasen 2002]); consequently, e.g. physics course as the potential source of various physical principles is not a part of their curriculum.

It is speculated that difference in variety between generated design concepts of the students of industrial design and mechanical engineering (SOPHY group using automatically generated chains of physical laws complementary basic schemata) would be statistically significant in case of tasks which would require use of physical principles other than mechanical ones. It is also speculated that difference in variety of generated design concepts of students of industrial design and mechanical engineering would be statistically insignificant in case of tasks that could well be satisfied using embodiment of mechanical physical principles. Our speculations are based on the results obtained by our first experiment, which confirmed the research hypothesis (i.e. the use of a chain of physical laws and complementary basic schemata offers greater possibilities for variation (i.e. embodiment of different solutions) than use of regular methods used by (student) industrial designers.) [Žavbi et al. 2011].

5. Conclusion

The design task was simple and there were no requirements (except for the main function) to be fulfilled by the generated concepts, thus allowing evaluation to be focused on variety rather than on the quality of fulfilment of additional requirements.
Additional experimentation is needed to confirm/reject the speculations expressed in the section Discussion. The methodology of the additional experimentation would be the same, only the content of the tasks would differ.
According to the results of the first experiment it is expected that computational tool SOPHY would be most effective when combined with designer's creativity (for manual embodiment) in problems concerning "idea in the product".

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