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USE OF KNOWLEDGE TWISTING FOR SYNTHESIS OF ALTERNATIVE ELEMENTARY SOLUTIONS

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1. Introduction

There is a positive correlation between the number of generated alternative product concepts and their quality [Andreasen&Hein 2000], so it makes sense to seek new formal methods that will enable the generation of alternative solutions. The crucial property of these methods should be the generation of a large number of alternative solutions without a combinatorial explosion. Many different approaches have been used to tackle the problem of generating alternative product concepts based on variations of physical laws, material, geometry and geometrical position. Let us mention only a few that are most commonly used.

Numerous authors [e.g., Höhne 1984, Pahl&Wallace 2002, Rodenacker 1970] use function structure in the design process. A weak spot of the design phase is the synthesis of function structure, which is essentially a mere trial and error process. In addition, a composed function structure does not allow the generation of a multitude of solutions that would function differently from what is planned by the function structure. There is also no empirical evidence of the absence of combinatorial explosion.

An alternative to function structure is a function-means tree, which is based on the function-means law as defined by [Hubka&Eder 1988]. Function-means tree is an extended function structure that allows the representation of both alternative decompositions and solutions for its functions [Hansen&Andreasen 2002]. The function-means tree thus allows several alternative concepts. However, this approach does not involve the use of equations of physical laws, only a schematic of the components (i.e. means). The set of possible component schemata in general is enormous, and this represents a problem regarding preparation and the amount of data required for computer support. The risk of a combinatorial explosion originates from the size of the schemata set and use of the tree synthesis method. However, no one has as yet undertaken to prove that a combinatorial explosion actually occurs when the function-means tree is used, exactly because of the large set of data.

This paper presents a method that does not require a prior synthesis of function structure to describe the functioning of a future product in component-neutral terms. In this way, we can avoid problems related to function structure that is synthesized in advance. Empirical analysis has shown that the use of this method does not lead to a combinatorial explosion. The method is based on the chaining of physical laws and complementary basic schemata [Žavbi&Duhovnik 1997].

2. Knowledge twisting

Knowledge twisting is defined as a kind of manipulation of *Physics P/Structure S/ Design D* (as mental objects) in order to achieve various *Function(s) F*. It is represented by a set of relations which can be identified in the framework of synthesis [Hansen&Žavbi 2002]: the *Physics P→Function F*, *Structure S→Function F* and *Design D→Function F* relations (Figure 1). The term “knowledge twisting” was originally proposed by Andreasen and it referred to Rodenacker's use of an "oil wedge" for the function "mixing of fluids".

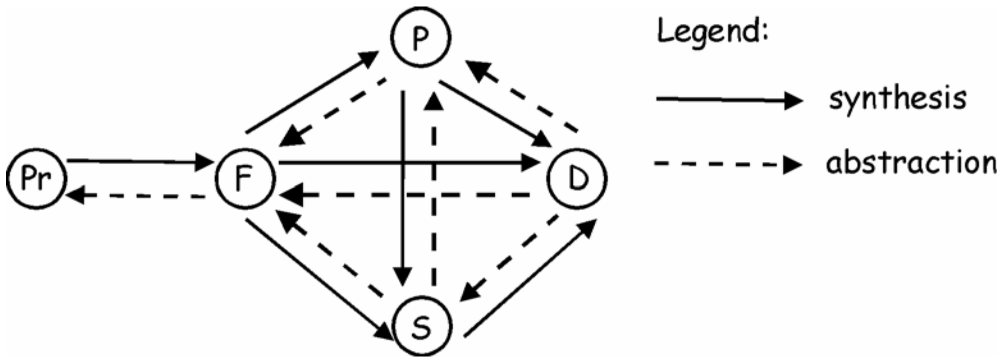

Figure 1. Framework of synthesis (Pr - Problem, F - Function, P - Physics, S - Structure, D - Design)

Use of the same physical law to fulfil various functions is the basic characteristic of the *Physics P→Function F* relation; *Physics P→Function F* is "one-to-many" relation.
A physical law is usually described by a relationship of the quantities:

quantity (*dependent*) = f(quantity (*independent*), quantities (*constant*)).

The manipulation represented by the *Physics P→Function F* relation is achieved by varying the (in)dependency of an equation's quantities (i.e. variation assigns (in)dependency to specific quantities, while others are kept constant). Versions of equations obtained by varying the (in)dependency of the quantities in an individual physical law were named "twisted equations". Figures 2, 3 and Tables 1, 2 illustrate two examples of such a variation. The use of variation of (in)dependency for various ways of fulfilling one function (i.e. measurement of viscosity) with a single physical law (i.e. capillarity) is described in [Rodenacker 1970].
The physical law, i.e., pressure definition: p (*dependent*) = f(F (*independent*), A), which was originally used to fulfil the function e.g. "generate force", will be used as an example (Figure 2 and Table 1). The physical law can also be used to fulfil a function e.g. "measure force".

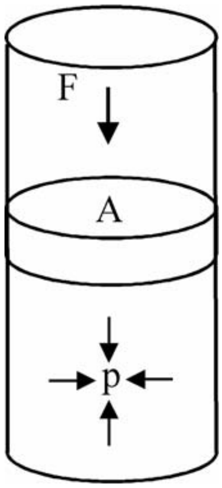

Figure 2. Pressure definition: p = f(F, A); (p-pressure, F-force, A-area)

When one identifies pressure as a stimulus, this means that a change in pressure affects the force. This combination can be used for fulfilling a function, e.g. "generate force." The combination of F (i.e. stimulus) and p (i.e. response) can be used for fulfilling a function, e.g. "measure force." In both cases, the law governing the behaviour is the definition of pressure.

The physical law, i.e., linear thermal expansion: $\Delta l = f(l_0, \alpha, \Delta T)$, which was originally used to fulfil the function e.g. “measure temperature”, will be used as an additional example (Figure 3 and Table 2). The physical law can also be used to fulfil a function e.g. “check material type”.

Table 1. Variation of a physical law’s (i.e., pressure definition) independent/dependent parameters

Independent parameter	Dependent parameter (response)	Constant	Function/Equation
p-stimulus	F	A	e.g. “generate force” F (*dependent*) = f(p (*independent*), A) initial equation
F-stimulus	P	A	e.g. “measure force” p (*dependent*) = f(F (*independent*), A) twisted equation
A	F	p-stimulus	e.g. “measure area” F (*dependent*) = f(A (*independent*), p) twisted equation
A	P	F-stimulus	e.g. “measure area” p (*dependent*) = f(A (*independent*), F) twisted equation
etc.	etc.	etc.	

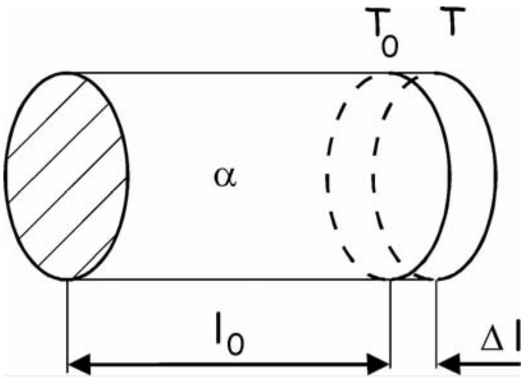

Figure 3. Linear thermal expansion: $\Delta l = f(l_0, \alpha, \Delta T)$; ($\Delta l$-length difference, l_0-original length, α-linear thermal expansion coefficient, ΔT-temperature difference)

When the coefficient of linear thermal expansion is identified as an independent parameter, this means that a change in the coefficient (i.e. a change in the type of material) affects the difference in length. This combination can be used for fulfilling a function, e.g. “check material type,” when using ΔT as stimulus. The combination of ΔT (i.e. stimulus) and Δl (i.e. response) can be used for fulfilling a function, e.g. “measure temperature.” In both cases the law governing the behaviour is that of linear thermal expansion.

Twisting thus expands the range of applicability of individual (i.e. initial) physical law. Operatively, this is manifested as an increased number of applicable physical laws (actually a set of physical laws and their twisted versions) that are used for synthesizing alternative solutions. In this way, equations with which physical laws are modelled can be systematically “twisted” and used to fulfil various functions.

Table 2. Variation of physical law's (linear heat expansion) independent/dependent parameters

Independent parameter	Dependent parameter (response)	Constant	Function/Equation
ΔT-stimulus	Δl	l_0, α	e.g. "measure temperature" Δl (*dependent*)= f(l_0, α, ΔT (*independent*)) initial equation
α	Δl	l_0, ΔT-stimulus	e.g. "check material type" Δl (*dependent*)= f(l_0, α (*independent*), ΔT) twisted equation
l_0	Δl	α, ΔT-stimulus	e.g. "check original length" Δl (*dependent*)= f(l_0 (*independent*), α, ΔT (*independent*)) twisted equation
etc.	etc.	etc.	

3. Method

To date, we are able to simply and systematically perform only the manipulation represented by the *Physics P→Function F* relation, which is achieved by varying the (in)dependency of equation's quantities. The variation was done manually on 139 initial equations of physical laws. The basic source for these equations is a catalogue that was composed by Koller & Kastrup [Koller&Kastrup 1994]. New equations obtained in this manner (i.e., twisted versions of initial equations) were added to the initial database of 139 equations. The total number of equations thus rose to 321.

In order to present the usefulness of the concept of the manipulation represented by the *Physics P→Function F* relation, we used an algorithm for chaining physical laws i.e. equations with which these laws can be written [Žavbi&Duhovnik 1997, 2001]. The chaining approach is based on the idea of binding physical laws and their complementary basic schemata (an abstract structure with certain geometry, geometric position and relevant environment represented by material and fundamental constants) via binding variables. A binding variable is a variable common to a physical law and its successor in a chain. The result of chaining is a chain, which describes the transformation of an input variable to an output variable (i.e., an abstract description of the mode of action). Chaining is regarded as a search for and synthesis of basic schemata into structures which are capable of realizing the required function. The existence of a relation between a physical effect and a structure basically enables the use of physical effects in designing. The chaining approach is described in details in [Žavbi&Duhovnik, 2001].

The algorithm [Žavbi&Duhovnik, 2001] is as follows:

(Step 1): *Deduce the characteristic, initial variable from the function of the technical system to be designed;*

(Step 2*): Search for all physical laws (i.e., equations) that contain characteristic, initial variable and use them to generate the successors of the root node such that they contain the remaining variable from the physical law.*

CONDITION:

IF

the generated node contains a variable from the sets of geometric, material and base variables

THEN

STOP the generation of successors of this node;

(Step 3): *For other nodes that do not fulfil the CONDITION, search for all physical laws that contain the variable of an individual node and generate their successors such that they contain the remaining variable from the found physical law;*

(Step 4) *Repeat step 3 until all leaf nodes fulfil the CONDITION.*

The description of the characteristic, geometric, material and base variables is as follows:

- the characteristic variable is a variable related to a function of a technical system to be developed;
- the geometric and material variables are variables related to geometry and material of a basic scheme that is complementary to a physical law;
- the base variable is the term taken from physics, in which it is postulated that all variables (with the exception of the basic ones) can be defined by the basic ones, which are: length, time, mass, electrical current, temperature, amount of substance and luminous intensity.

When chaining, the following limitation needs to be considered:

- Only variables of the opposite type can be used to search abstractions (variable X-*stimulus* can be used to find the physical law containing variable X-*response*, and vice versa). The variables in the database of physical laws have designations (stimulus or response), which serve to indicate causal relations.

4. Results

This section presents part of the results that were obtained using the above method.
For the pattern *specified input (i.e. pressure p)/unspecified output* (Figure 4), the algorithm generates 446 elementary product concepts (with a set of 139 initial equations) and 3822 elementary product concepts (with a set of 321 initial and twisted equations), which is about 8 times more alternative product concepts for pressure measurement when knowledge twisting is taken into account. The histogram presents the distribution of product concepts with respect to the number of equations and complementary basic schemata that are contained in an individual alternative solution (Figure 5).

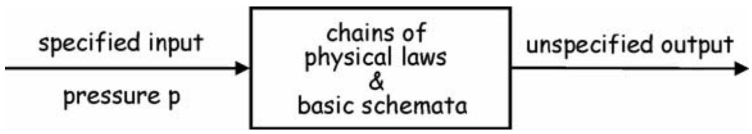

Figure 4. *Specified input* (i.e. pressure p)/*unspecified output* pattern

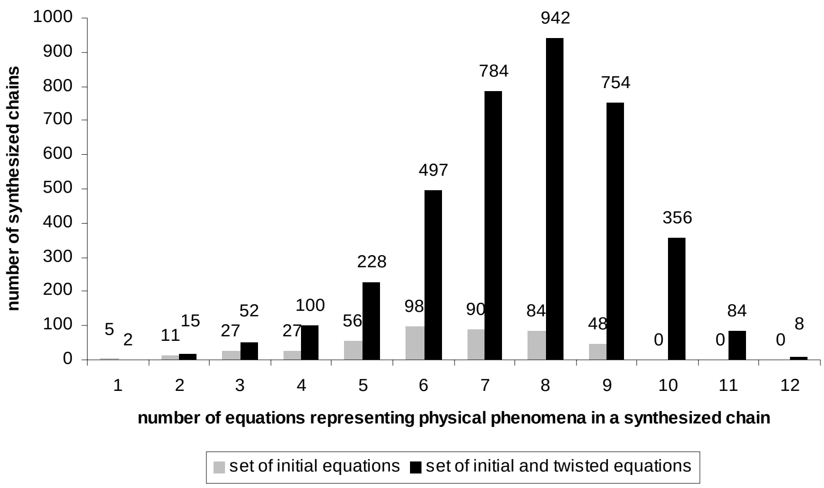

Figure 5. Histogram of generated product concepts of the s*pecified input* (i.e. pressure p as the independent quantity)/*unspecified output* pattern with two different sets of equations (139 and 321 equations, respectively)

The main message of the histogram is the absence of a combinatorial explosion. Figure 6 presents one of the possible solutions: a product concept with two equations describing the definition of pressure and spring deformation, with the complementary basic schemata. The chain represents the concept of pressure measurement which involves transformation of pressure into a force that causes spring deformation.

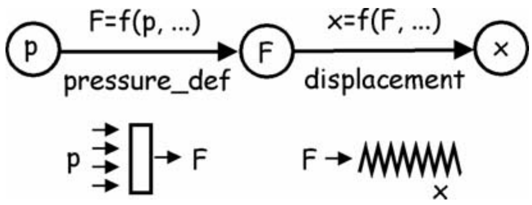

Figure 6. Example of a synthesized concept solution with two physical laws (i.e. relation between force and pressure and relation between force and displacement) for the *specified input* (i.e. pressure p)/*unspecified output* pattern. The basic schemata that are complementary to physical laws are shown below; p - pressure, F - force, x - displacement

The pattern of *unspecified input/specified output (i.e. pressure p)* is characteristic of e.g. pumps (Figure 7).

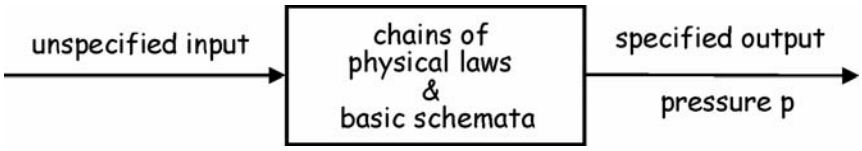

Figure 7. *Unspecified input/specified output* (i.e. pressure p) pattern

If a set of 139 initial equations is used, 586 elementary product concepts are generated while with 321 initial and twisted equations there are 9337 elementary product concepts and that is approximately 16 times more alternative pump concepts. In this case as well, the histogram demonstrates an absence of a combinatorial explosion (Figure 8). Figure 9 presents one of the possible solutions, i.e., a chain of three equations that enable the transformation of electric current to pressure, as well as the complementary basic schemata. The electric current in the coil generates a magnetic field, and this in turn generates a force in the piston rod. The force is then transformed to pressure by the piston.

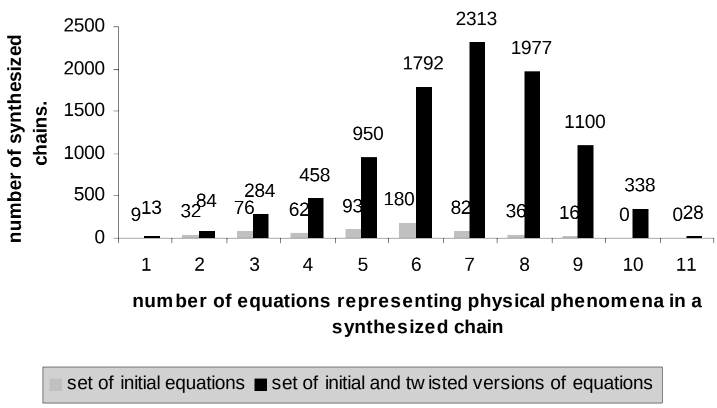

Figure 8. Histogram of generated product concepts of the unspecified input/specified output (i.e. pressure p as the dependent quantity) pattern with two different sets of equations (139 and 321 equations, respectively)

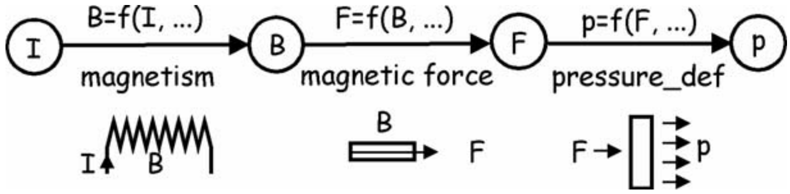

Figure 9. Example of a synthesized concept solution with three physical laws (i.e. magnetism, magnetic force and relation between pressure and force) for the *unspecified input/specified output* (i.e. pressure p) pattern. The basic schemata that are complementary to physical laws are shown below; I - electric current, B - magnetic field, F - force, p - pressure

5. Conclusion

Chains of equations and complementary basic schemata represent the elementary product concepts, which enable various embodiments. The transition between elementary product concepts and embodiments is not yet formalized; it is left to the design engineer. The formalisation of the transition is a part of future evolution of the method, which will also improve the quality of the concepts.

By using knowledge twisting, the set of equations (i.e., physical laws) is increased from 139 to 321. Knowledge twisting (represented by the *Physics P→Function F* relation) thus expands the applicability of the same physical law and consequentially the number of generated alternative elementary product concepts (Figures 5 and 8). Such straightforward approach is temporarily not possible for the other two relations (represented by the *Structure S→Function F* and *Design D→Function F* relations) of the knowledge twisting and its synthesis remains an open question.

The most important result is the fact that a combinatorial explosion did not take place in any of the cases (e.g., Figures 5 and 8). The absence of a combinatorial explosion is one of crucial properties of useful methods for generating alternative product concepts.

Knowledge twisting by chaining physical laws thus increases our chances of generating good product concepts, as the quality of the concepts increases with their number.

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