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IMPACT OF KNOWLEDGE TWISTING ON COMBINATORIAL EXPLOSION

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Abstract

Many different approaches have tackled the problem of generating alternative solutions to problems based on variations of physical laws, material, form, dimensions and topology (i.e., geometrical position). The algorithm for chaining initial physical laws is known not to cause a combinatorial explosion. Because there is a correlation between the number of generated alternative solutions and their quality, it is reasonable to search for new methods for generating alternative solutions. The paper thus presents the knowledge twisting approach (i.e. variation of (in)dependence of parameters in a physical law and reallocation of receptor/effector wirk elements in a complementary organ), combined with chaining of physical laws. Knowledge twisting expands the applicability of initial physical laws, but it could also increase the risk of occurrence of a combinatorial explosion. However, the analysis described in this paper showed that there is no such risk.

Keywords: synthesis, knowledge twisting, chaining of physical laws, combinatorial explosion

1. Introduction

Many different approaches have tackled the problem of generating alternative solutions to problems based on variations of physical laws, material, form, dimensions and topology (i.e., geometrical position).

Considering the objective, which is to generate as many alternative solutions as possible in order to be able to select those which are truly the best ones, it also makes sense to seek new formal methods that will enable the generation of alternative solutions. It is believed that knowledge twisting combined with chaining of physical laws is one such method. The chaining of physical laws is based on searching, and a typical problem associated with searching is the problem of combinatorial complexity. For non-trivial problems, the number of alternatives is so high that the problem of complexity frequently becomes critical.

In order to shed some more light on product synthesis, a broader term, "framework of synthesis" was proposed by Hansen&Žavbi [1]. The framework links the stepwise determination of the artifact's characteristics during the design process to different ways of carrying out functional reasoning; it consists of mental objects and operations between them. They are described as follows [1]:

- Pr (Problem): A design problem, which is based on a perception of a need;
- F (Function): Function, i.e. a thought, idea or intention to design something, or a more crystallized statement about the action behaviour of the product to be designed. F is not just a functional aspect of a product, but the main function, which makes the product

purposeful and gives it *raison d'être*. F may be expressed verbally as an effect: "create heat" and may be related to an object: "make arm move";

- D (Design): Design, which may be specified as a model of the parts to be produced and their assembly process;
- S (Structure): Structure, i.e. an imagine or model of organ structure, which carries the functionality F. The structure may be more or less concrete and detailed and specified by its organ relations and organ characteristics, for instance as a product model;
- P (Physics): The view upon a design or structure, which explains the physical effect of realizing the functions. The physical effect may be represented by a physical law or by models, e.g. schematics or equations. A physical effect is either expected, Pe, to realize the required function, or it is a predicted physical behaviour, Ps, of a structure or design.

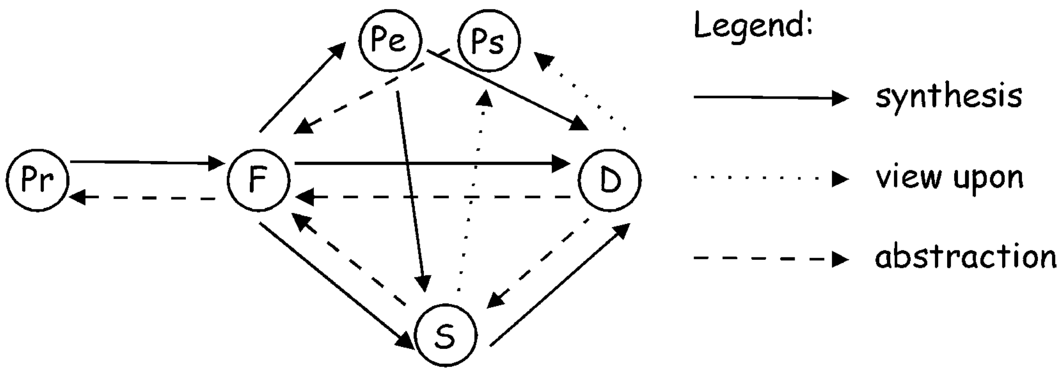

Figure 1. Framework.

Between the above mental objects, three types of mental operations related to synthesis were proposed:

- Carrying out a synthesis step, e.g. Pr→F or F→S or S→D;
- Creating a view upon the structure or design, e.g. S→P or D→P;
- Making an abstraction (e.g. of a design into its structure); e.g. D→S or S→F or F→Pr.

The set of identified objects and operations leads to the framework of synthesis shown in Figure 1. The framework can also be seen as a map which shows how and where to go from the start, e.g. from a required function, to the final position, e.g. product structure and form.

The purpose of this paper is to present the concept of knowledge twisting and its influence on the generation of conceptual chains, primarily regarding the risk of a combinatorial explosion, in order to establish the applicability of chaining of physical laws by using initial and twisted versions of physical laws. According to Andreasen&Hein [2], there is a correlation between the number of generated alternative solutions and their quality. On the other hand, the occurrence of a combinatorial explosion must be prevented, since this brings about an unmanageable multitude of solutions.

1.1 Knowledge twisting

One of the activities, which can be identified in the framework and is hidden in the P→F relation, is called "knowledge twisting" as proposed by Andreasen [3]. Knowledge twisting is a kind of manipulation of a Physics P (as a mental object) in order to achieve new Function(s) F.

It is believed that there are two types of knowledge twisting. One type of knowledge twisting is carried out by variation of a physical law's independent/dependent parameters (i.e. variation assigns (in)dependence to two different parameters while others are kept constant quantities), which reallocates receptor/effector wirk elements in a complementary organ and enables fulfillment of new functions. According to the Theory of Domains [4, 5, 6], organs are active elements which create effects (based on physical laws) and represent structural description of a design. The areas on organs which receive stimuli or deliver the response are called receptor and effector wirk elements, respectively [6]. Stimulus is characterised by independent/constant and response by dependent parameter in a physical law. The basic characteristic of knowledge twisting is that the physical law remains the same, regardless of the function it fulfils. But it has to be kept in mind that not all variations are physically possible within a single physical law.

Figures 2 and 3 and Tables 1 and 2 illustrate two examples of such a variation.

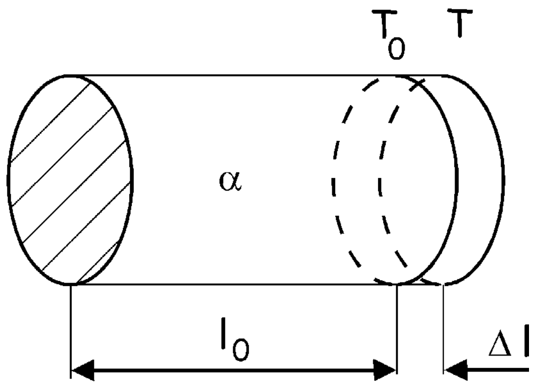

Figure 2. Linear heat expansion: $\Delta l = f(l_0, \alpha, \Delta T)$; (Δl-length difference, l_0-original length, α-linear thermal expansion coefficient, ΔT-temperature difference).

Table 1. Variation of physical law's (linear heat expansion) independent/dependent parameters.

Independent parameter	Dependent parameter (response)	Constant	Function
ΔT-stimulus	Δl	l_0, α	e.g. "measure temperature"
α	Δl	l_0, ΔT-stimulus	e.g. "check material type"
l_0	Δl	α, ΔT-stimulus	e.g. "check original length"
α	ΔT-stimulus	l_0, Δl	not possible
etc.	etc.	etc.	

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. And when one states that a temperature difference cannot be a response to a change in the coefficient of linear thermal expansion, this means that the temperature difference cannot be affected by it.

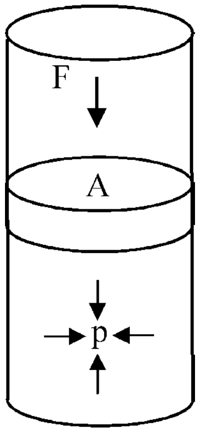

Figure 3. Pressure definition: p = f(F, A); (p-pressure, F-force, A-area).

Table 2. Variation of a physical law's (pressure definition) independent/dependent parameters.

Independent parameter	Dependent parameter (response)	Constant	Function
p-stimulus	F	A	e.g. "generate force"
F-stimulus	p	A	e.g. "measure force"
A	F	p-stimulus	e.g. "measure area"
A	p	F-stimulus	e.g. "measure area"
p-stimulus	A	F	not possible
etc.	etc.	etc.	

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. And when one states that a change in surface area cannot be a response to a change in pressure, this means that surface area cannot be affected by it.

Twisting thus expands the range of applicability of individual (i.e. initial) physical laws. 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 conceptual chains.

The variation of (in)dependence of parameters is analogue to the Rodenacker's systematic study of physical processes [7].

1.2 Open questions about knowledge twisting

The other part of knowledge twisting seems more creative in nature, it is hard to tackle and still lacks any kind of support. Several research questions have been posed and addressing them will require further research. These questions arose while studying Rodenacker's example of an "oil wedge" [3, 7], (i.e., a structure of wirk elements), which was used to clarify the derivation of new applications – new functions (e.g., mixing of fluids, making a foil, Figure 4) based on the oil wedge and its complementary physical law:

- Are the physical laws governing, e.g., mixing of fluids and making of foil, really the same as in the case of an oil wedge?

- What are the parameters which affect, e.g., thickness of foil, uniformity of thickness and corrugation of foil and how they are related?
- Could one say that this part of knowledge twisting provides new functions based on the same structure of wirk elements or parts but different/altered/supplemented physical laws which are found via this structure?
- Is this a way to find new applications (i.e. functions) for which some physical laws are difficult to describe (and are as such inaccessible to physical reasoning)?
- Does this second part of knowledge twisting in fact corresponds to relations D→F and S→F found in the proposed framework of synthesis?
- What came first: design/experiment or a physical law [3], may we discuss them separately?

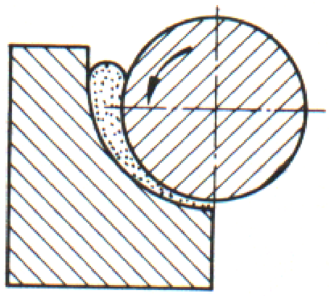

Figure 4. Mixing [7].

2. Chaining

Chaining of physical laws is one way of synthesizing solutions and can be identified in the relation P→S. The concept of use of physical laws is based on the fact that all technical systems function according to physical laws. The principle of chaining is illustrated in Figure 5.

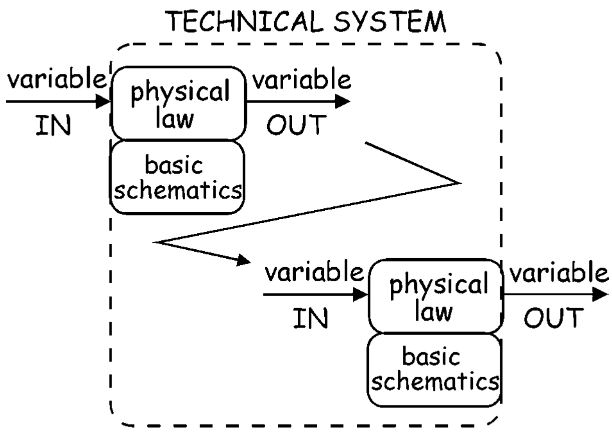

Figure 5. Chaining of physical laws and their complementary basic schematics via binding variables [8].

The chaining approach is based on the idea of binding physical laws and their complementary basic schematics (i.e. sets of wirk elements) via binding variables [9, 10]. Chaining is based on the observation that many technical systems contain a chain of physical effects. 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 schematics 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 (e.g. [1]). The chaining approach is described in details in [10].

As far as the input and output variables of technical systems are concerned, we distinguish between three general patterns [9]. The most frequently used is the *specified input/specified output* pattern, in which the designer is required to determine the input and the output variable of a technical system in advance. However, this method also narrows down the range of alternatives, because not all physically possible solutions and combinations of the input and output variables are known in advance. The two other possible approaches are the *specified input/unspecified output* pattern and the *unspecified input/specified output* pattern. In contrast to the first pattern, the latter two offer greater possibilities for innovations. If one of the variables (input or output) of a technical system is unspecified in advance, it is possible to generate a larger set of conceptual design chains.

2.1 Chaining of twisted versions of physical laws and combinatorial explosion

Chaining is performed according to the supplemented chaining algorithm as presented in [8]. When the problem of chaining is discussed, search-related problems are mainly addressed, because the problem of generating conceptual design chains is generally one of searching for a path from the initial node to the goal node, where the initial node is the input/output variable and the goal node is the output/input variable of a technical system. Physical laws represent the rules for connecting two nodes, while the path from the initial node to the goal node represents the conceptual design chain of a product.

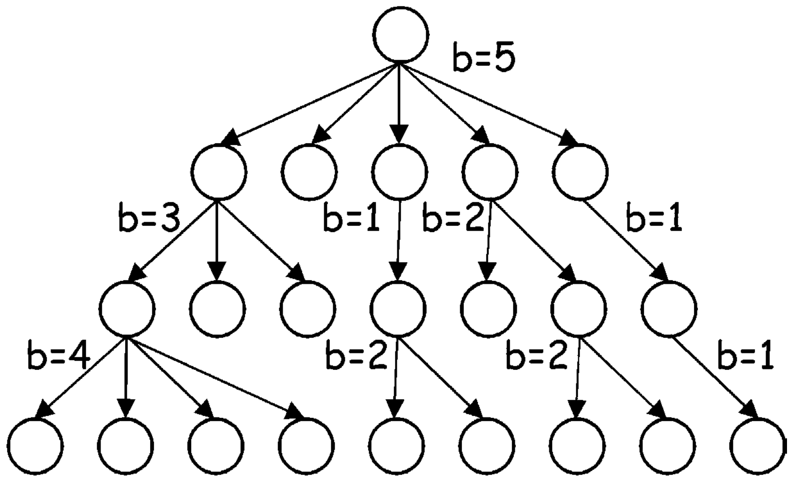

Figure 6. An example of non-uniform branching factor.

A typical problem associated with searching is one of combinatorial complexity. For non-trivial problems, the number of alternatives is so high that the problem of complexity frequently becomes critical – let us see why. If each node has b successors (i.e. branching factor b), then the number of paths with length l from the initial node is b^l. The set of paths thus grows exponentially with path length, which leads to a combinatorial explosion. Naturally, the previous explanation is based on a simple case of a uniform branching factor. If physical laws are chained, the branching factor varies between the nodes (each input/output variable can generate various numbers of output/input variables with various numbers of physical laws, Figure 6) and the length of conceptual design chains also varies. However, the risk of a combinatorial explosion remains [8].

3. Comparison of synthesized chains using initial and twisted versions of physical laws

All twisted versions were written for each initial law (see Tables 1 and 2) and were added to the database. The database thus contains 321 initial and twisted versions of physical laws. For this database, it is now necessary to check whether a combinatorial explosion could occur. The methodology which was used for a set of initial physical laws was also used for the case of additional twisted versions of physical laws.

For example, Figure 7 shows the number of chains which are synthesized using a computer program based on the chaining algorithm. The specified input/unspecified output pattern was used, where force is the input, while the output is unspecified. The number of chains increases with an increase in the number of initial and twisted versions of physical laws. Changes in the number of synthesized chains are not important, because the magnitude of changes depends on the sequence of writing individual laws in the database. It is important, however, to prevent a combinatorial explosion from occurring, since the use of the entire database synthesizes 2094 chains; this is a lot, but far from a combinatorial explosion. The length of chains (i.e., the number of physical laws in a chain) varies from 1 to 11.

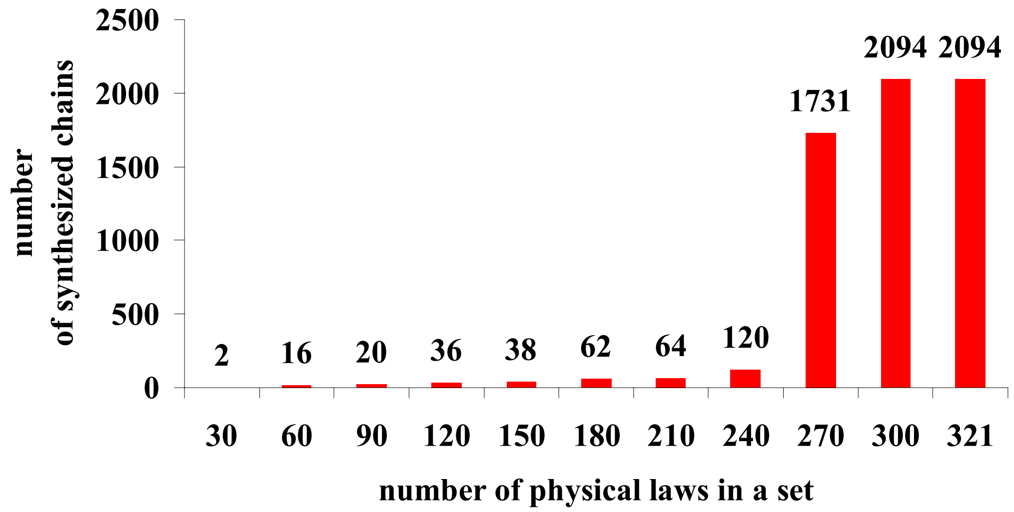

Figure 7. Number of generated chains vs. set size for force F as independent variable in the specified input/unspecified output pattern.

For example, Figures 8, 9 and 10 show histograms of chains generated according to the specified input/unspecified output pattern, where the input consists of force F, heat Q and magnetic field B as independent variables, respectively. In all cases, chains are shown which are generated by both the set of initial physical laws and the set of all physical laws (i.e. their initial and twisted versions).

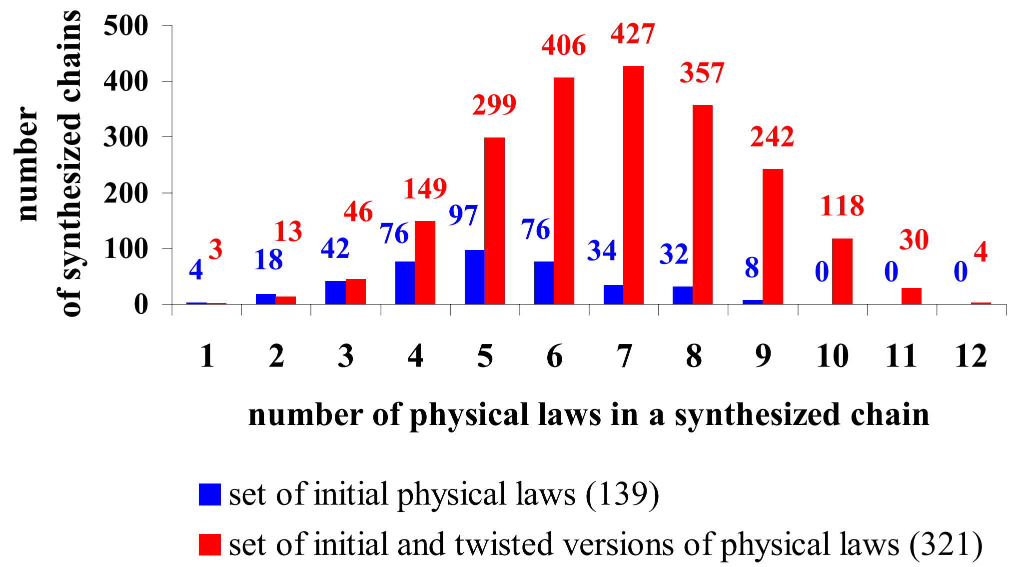

Figure 8. Histogram of synthesized chains for force F (Σ = 387 for the set of initial physical laws and Σ = 2094 for the set of initial and twisted versions of physical laws).

In the process of testing the chaining algorithm with a set of initial and twisted versions of physical laws, many chains were synthesized for all three patterns of input/output variables and with various input/output variables. The most important result is the fact that a combinatorial explosion did not take place in any of the cases.

The next step of testing the applicability of chaining of physical laws is systematic verification of the reasonableness of individual combinations of physical laws in synthesized chains, since some researchers have drawn attention to the possibility of senseless combinations. For example, Bracewell warned about this phenomenon with respect to the TRIZ approach [11].

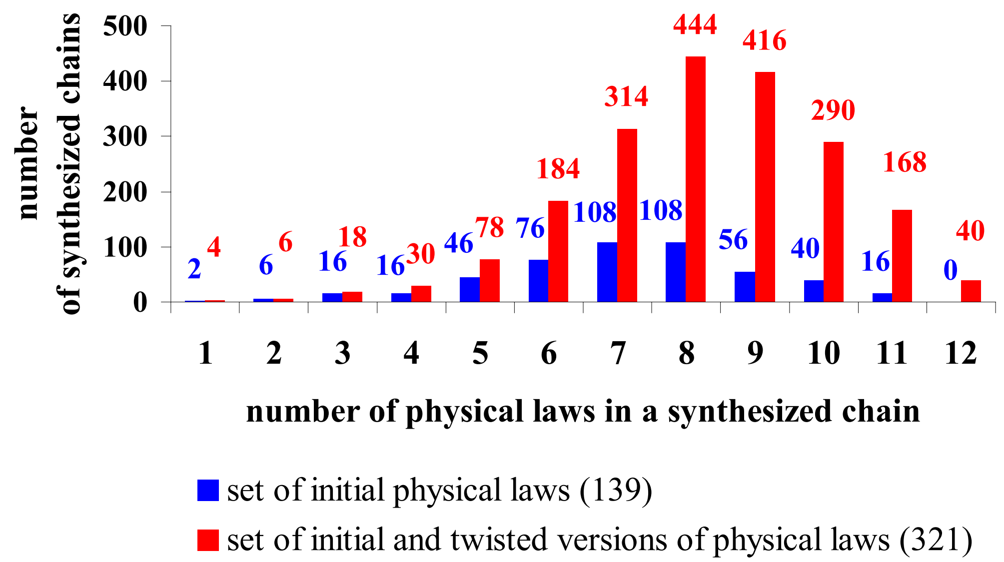

Figure 9. Histogram of synthesized chains for heat Q (Σ = 490 for the set of initial physical laws and Σ = 1992 for the set of initial and twisted versions of physical laws).

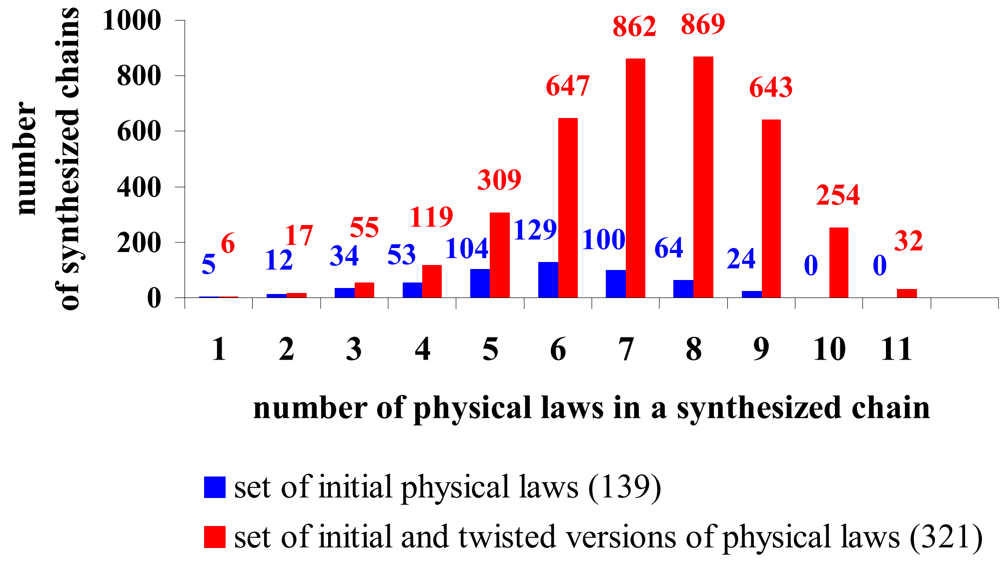

Figure 10. Histogram of synthesized chains for magnetic field B (Σ = 525 for the set of initial physical laws and Σ = 3813 for the set of initial and twisted versions of physical laws).

4. Conclusions

Many different approaches have tackled the problem of generating alternative solutions to problems based on variations of physical laws, material, form, dimensions and topology (i.e., geometrical position) (e.g., [7, 12]). It is believed that knowledge twisting combined with chaining of physical laws is one such approach.

Regardless of many open questions related to knowledge twisting, analysis of chaining makes sense, because it applies only to the part of knowledge twisting (i.e., variation of (in)dependence of parameters and reallocation of receptor/effector wirk elements in a complementary organ), which is clear. One immediately notices that twisted versions of physical laws increase the size of the database from 139 to 321 physical laws. Knowledge twisting thus expands the applicability of initial physical laws and consequentially the number of generated alternatives, but at the same time also increases the risk of a combinatorial explosion, because chaining of physical laws is a search-based activity. Therefore, analysis not only makes sense, but is actually necessary.

The analysis was expected to show that a combinatorial explosion does not occur and thus to confirm the applicability of chaining of physical laws also for cases in which both initial physical laws and their twisted versions are used. The reason for such predictions was seen in the nature of the algorithm, primarily in the condition that determines the cessation of chaining. This is because it stipulates stoppage of chaining if a generated node (i.e. variable) contains a variable from the sets of geometric, material and base variables; in twisted versions of physical laws, most variables are of this type.

The analysis showed an increase in the number of synthesized chains and only a very small increase in the number of physical laws per individual chain, but no risk at all of a combinatorial explosion. The results of the analysis are seen as an empirical proof that chaining based on the set of initial and twisted versions of physical laws is not problematic from the viewpoint of combinatorial explosion.

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