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Conceptual design of technical systems using functions and physical laws

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Abstract

Since the operation of technical systems can be explained using physical laws, why then might we not use them explicitly in designing these systems? The characteristic initial binding variable, with which appropriate physical laws are sought, first needs to be extracted from the function of the future technical system. If there are several appropriate physical laws (i.e., operators), we evaluate them using the Analytic Hierarchy Process (AHP) method. The most suitable is then selected with regard to the chosen criteria based on design requirements. When one physical law is not sufficient for the design of a technical system, several laws are linked together using binding variables to form a conceptual chain (i.e., macro-operator). Such a chain does not only contain supporting physical laws; physical laws indirectly introduce basic models of shape, their basic topology, geometry, and basic material properties into the chain. A prototype computer-aided design system is based on the prescriptive conceptual design model presented below.

Keywords: Function; Binding Variable; Chaining of Physical Laws; Operator; Macro-operator

1. INTRODUCTION

In recent years, the design process as one of the key phases of product development, that is, technical system development (Hubka, 1976; Dym, 1994), has been the object of much interest from researchers in different fields: from mechanical engineering through electrical, computer and civil engineering and architecture, to psychology, philosophy, etc.

There are several reasons for such intense interest:

- In general, the design process is a consequence of human creativity, which, with the development of artificial intelligence, genetic algorithms and neural networks, are themselves becoming subjects of increased interest in natural science and technical circles (Saaty, 1988; Gero et al., 1995; Stefik, 1995).
- A trend of increase in the ability to produce technical systems can be noticed worldwide; therefore, companies can gain or maintain a competitive advantage only through successful development of new technical systems. In our usage, a "new system" is one based on physical laws that until then had not been employed in a certain field, or else based on new combinations of previously used physical laws.
- An inadequately described design process hinders effective development of computer-aided tools in designing technical systems. This is evident from the fact that the development of such tools for individual phases of product development has proceeded in exactly the opposite direction from the succession of product development phases (Whitney, 1992, 1993, 1995). This is because drafting tools were developed first; these were used to prepare workshop documentation, which comes at the end of the design process. Three-dimensional (3D) modellers with FEM tools were developed later, but we still do not have appropriate tools in the conceptual design phase, even though the conceptual design phase precedes all other phases of product design (apart from the specification phase).
- The majority of costs (80%) in the life cycle of a technical system are determined in the design phase (Hubka, 1976; Whitney, 1992; Koller, 1994; Wallace, 1997).

The LECAD laboratory began to develop its first model of technical-system design in 1989. The model reached the prototype stage in 1992 and by 1995 was installed into a proto-

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type design environment (Duhovnik & Žavbi, 1992; Žavbi & Duhovnik, 1995, 2000). This model designed a technical system on the basis of the working principles, which were extracted from the existing components. The new feature here was concurrent growth of the function structure. The function structure-based conceptual design models, which were used until then, were characterized by a rigid function structure, which had to be produced in advance, manually, and, in addition, such structure also predetermined the classes of components which could be used by the model. However, a predetermined component class prevents the use of component classes that simultaneously fulfill a different number of functions than those predetermined by a rigid function structure. This limitation strongly restricts the utility of such models (Žavbi & Duhovnik, 1995). Our model was applied to the conceptual design of mechanical-drive units; its use resulted in an appropriate function structure incorporating the corresponding working principles and all the necessary components (gears, belts, pulleys, chains, sprockets, shafts, bearings, etc.).

However, its limited ability for conceptual design was soon noticed. This was due to the model being based on descriptions of the existing components, with working principles derived from them. If a working principle was not materialized in an existing component, the component could not be used.

We, therefore, wanted to produce a prescriptive model for the conceptual design of technical systems that would involve an explicit use of physical laws based on macroscopic material properties (size, mass, elasticity modulus, specific heat, resistance, refractive index, etc.) and would make possible designing from scratch. It was not our intention to explain material properties, but rather to use physical laws in the service of designing technical systems. The new model was also expected to surpass the shortcomings of the first model, which was, as noted, based on the existing components and working principles derived from them.

It must be noted that the term "physical law" is used here in its widest sense, that is, as a relation that describes how macroscopic material properties depend on external conditions.

In conceptual design, at least four sources can be identified that make an essential contribution to technical systems' degree of innovation. These are physical laws, topology, and the shapes and materials of elements that apply physical laws:

- Physical laws (e.g., in the majority of cases, the moving magnet and moving coil in gramophones were replaced by lasers).
- Topology (e.g., the introduction of split system air-conditioning devices).
- Geometry (e.g., the shape of automobile bodies has become more aerodynamic).
- Materials (e.g., the use of PET instead of glass in manufacturing of packaging for drinks).

The existing methods of conceptual design obscure the fact that creative design draws from several sources. Therefore, these are not treated directly and the connections between them are not sought, which limits the efficacy of the existing design approaches, methods, and models.

The basic and richest sources for design are physical laws (Figure 1). The richest because each physical law can be materialized in several topologies, each topology in several forms and each form in several materials. The selection of a physical law, therefore, offers an opportunity to design a multitude of technical systems that differ in form, topology and material, but which share the same physical law. Let us take roller bearings as an example: they all have the same physical law in common (rolling friction), but the rolling elements differ in shape (ball, cylindrical roller, spherical roller, tapered roller), topology (radial, radial-axial, axial), and material (various types of steel and ceramics). On the other hand, physical laws are the basic source because no technical system operates contrary to them. The results of designing from scratch or creative design, therefore, always range within the valid limits of physical laws (Žavbi & Duhovnik, 1997, 2000). Operation of existing technical systems can be explained using physical laws; why, then, might we not use them to design such systems?

Interesting approaches in this area have been described by Williams (1989, 1992), Bratko (1993), Ishii and Tomiyama (1996), Sushkov et al. (1996), and Chakrabarti et al. (1997).

Williams' approach to innovative conceptual design is based on the idea that all of the possible interactions between the variables based on the components stated in the problem, as well as all of the possible interactions that are technologically available (i.e., the existing components are capable of), first need to be identified for the required task. The interactions are established using "first principles," which are essentially physical laws in the wider sense of the word. The path in the graph that connects the existing interactions with the required functioning (expressed through variables) of the technical system represents the conceptual design of a technical system, which includes the components being used and the configuration itself.

Bratko describes an idea for innovative design based on a function that is given through examples of behavior of a future technical system, and a description of the function-

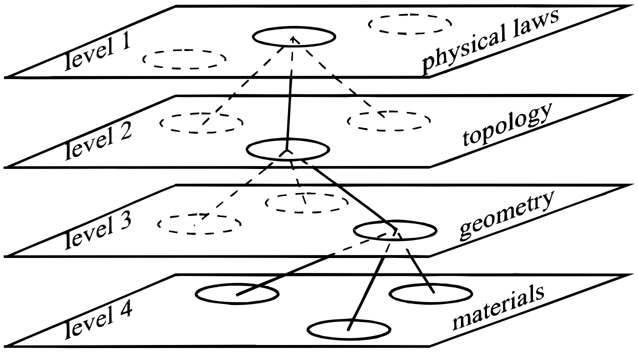


Fig. 1. Design sources.

ing of technologically available components (using qualitative physics) and Inductive Logic Programming (ILP) as conceptual design method.

The approach of Ishii and Tomiyama initially assumes a predetermined function structure, which is supplemented with a state transition graph. On the basis of such a graph, an automatic modeller, part of which is based on Qualitative Process Theory (QPT) (Forbus, 1984), selects appropriate physical laws that can ensure the state transitions (transformations of variables) listed in the above-mentioned graph.

Chakrabarti takes it as his goal to produce a computer-aided system for the generation, evaluation, and optimization of the conceptual design of micromechanical sensors that are based on the chaining of elementary models. Elementary models are presented with a *signal—media—message* schematic; thus, for example, a spring is presented with the schematic *force—spring—position*.

The question may be raised as to why we as well did not use qualitative modelling methods. The reason for this is our assumption that merely the abstractions of physical laws and information on the influence of an individual variable on another variable will suffice for the conceptual design of technical systems. Qualitative models do provide information on the direction of changes (+,−,0), but due to qualitative summation a number of ambiguous behaviors may appear in their use, which leads to a combinatorial explosion (Bratko et al., 1989) that is not a consequence of the plethora of combinations of the large number of various physical laws. In addition, in order to evaluate the obtained conceptual designs and make a final decision on selecting one or a small number of the generated conceptual designs for further development, an analysis of the extent of the influences of individual variables will be necessary, and this is possible with quantitative models. For example, in the case of conceptual design of a laser deflection probe (Diaci, 1996), it was necessary to check whether it is at all possible to measure the deflection of a laser beam due to its refraction in air compression using the technologically available components; it turned out that a special opto-electronic technical system, a quadrant photodiode, was necessary and was, therefore, developed later (Diaci, 1996).

1.1. Review of basic terms

The purpose of this subsection is to review and briefly explain terms used in the paper.

Function: The purpose of the future technical system expressed in a neutral manner, that is, without indicating any solutions. Examples: sound detection, torsional moment transfer, maintenance of a certain liquid level, etc. The terms *required function* or *main function* are also used.

Physical law: The term is here used in its widest sense; it represents the functional connection between variables, geometrical parameters, and material and basic constants. These also have an expressive value, due to which they can actually be used for design. For example, the refractive index introduces light in conceptual design, geometrical parameters give information on the basic geometry, and material and basic constants provide information on participating materials or the environment. The terms *relation* and *working principle* are also frequently used. It should also be emphasized that, in general, mere abstractions of physical laws (no operators, only parameters) suffice for the central part of a conceptual design. This paper, therefore, uses the terms *physical law*, *relation*, *working principle*, and *abstraction* of physical law as synonyms.

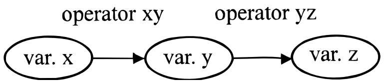


Fig. 2. Function of the operator.

Operator: It is an alternative term for a physical law. In general, operators are used for the transformation of one problem state into another (Figure 2).

Base variable: The term is taken from physics, in which it is postulated that all parameters (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 (Giancoli, 1988).

Binding variable: Variable common to a physical law and its successor in the conceptual design chain.

Chaining: Searching for a successor physical law in the conceptual chain using the binding variable. The binding variable may be used to find a physical law that contains such a variable, but it needs to be of the opposite type, for example, variable-cause can find variable-effect or *vice versa*.

Conceptual design chain: A chain of physical laws that fulfill the required function partially or entirely.

Macro-operator: It is an alternative term for a conceptual design chain. It consists of operators (i.e., physical laws). In general, macro-operators enable the use of several operators at the same time (Figure 3).

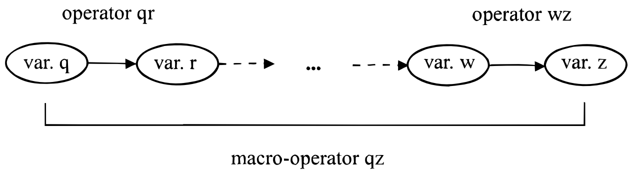


Fig. 3. Function of the macro-operator.

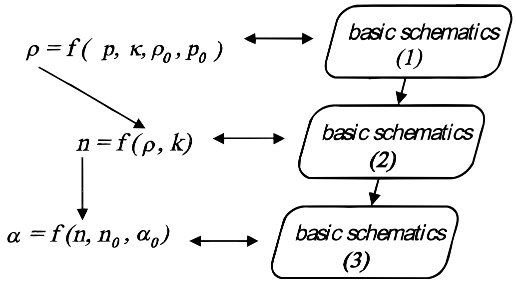


Fig. 4. Idea of chaining of the abstractions of physical laws with the complementary basic schematics.

2. FORMING AN ALGORITHM

As was mentioned in the Introduction, the LECAD laboratory had already developed a model for the design of technical systems, which was applied to the conceptual design of mechanical-drive units.

However, we discovered relatively early on that the model was limited because it was based on the description of the existing components, with working principles derived from them. If a component in which a relation is materialized does not yet exist, such a relation cannot be used in conceptual design: it cannot be used for designing from scratch. This limitation could be eliminated with an improved conceptual design model, which is based on the idea presented in Figure 4.

2.1. Algorithm

The following algorithm (Žavbi, 1998) was based on the above idea:

STEP 1. *Deduce the characteristic, initial variable from the function of the technical system to be designed;*

STEP 2. *Search for all abstractions of physical laws 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 found abstraction of 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 abstractions of physical laws that contain the variable of an individual node and generate their successors such that they contain the remaining variable from the found abstraction;*

STEP 4. *Repeat step 3 until all leaf nodes fulfil the CONDITION.*

When chaining, the following two limitations need to be considered:

- Only variables of the opposite type can be used to search abstractions (variable X-cause can be used to find the physical-law abstraction containing variable X-effect, and *vice versa)*. The variables in the database of physical laws have designations (cause or effect), which serve to indicate causal relations.
- No physical law may be repeated in any individual conceptual design chain (i.e., generated path). Possible problems arising due to this requirement are eliminated by using the design principle of variation of the number of physical laws (Pahl & Beitz, 1993). This design principle has not been implemented, yet. There are many examples in practice in which an individual physical law appears several times (e.g., multistage drive units, multiple-disc clutches, trusses, etc.).

If there are several appropriate relations, the chain may be split off and may be continued in the direction of more suitable physical laws. A suitability assessment is performed using the Analytic Hierarchy Process (AHP) prior to each continuation of chaining, since in this manner one can prevent a combinatorial explosion and guide conceptual design with regard to design requirements (Saaty, 1988).

The correctness of the algorithm can be tested with reconstruction of the existing technical systems, or the conceptual design of not yet existing, but physically possible ones.

2.2. Conceptual design

2.2.1. *Entry of the initial binding variable*

An interpreter is intended for the setting up of the initial binding variable with which the conceptual design of a technical system begins. This variable is used to find the relations which can become part of future technical systems.

In general, the following combinations are possible of input and output variables:

Input	Output
Known	Unknown
Known	Known
Unknown	Known

The first case occurs when a design engineer wishes to research the effects of a known input variable. For example, data on pressure variation is available and now the design engineer is interested in establishing what it can cause; such is the case of a laser deflection probe (Diaci, 1996; Žavbi & Duhovnik, 1997).

The second case arises when a design engineer actually searches for a direct or indirect transformation between two known variables. Such is the case of a piezo actuator in which *voltage U* is the input variable, while *force F* is taken as the output variable (Herakovič, 1996).

The third case arises when an engineer wishes to design a technical system that will be capable of generating a variable in some way, for example, *voltage*. However, it is only possible at the end of the conceptual design process to establish how and in how many different ways this can be done.

At the start of a conceptual design, one often first describes a phenomenon verbally, and only later extracts its characteristic variables. Thus, we first spoke of mechanical shock wave detection, and only later proceeded to extract characteristic variables such as pressure, density, and temperature. In the case of a piezo actuator, variables that were used to begin conceptual design were stated explicitly at the very beginning.

If one of our goals is also to produce a prototype computer program that would be capable of conceptually designing technical systems on the basis of input or output variables or both, then two methods of treating initial binding variables are available. The first one is explicit entry of these variables, while the second one is the selection of phenomena with a predetermined set of characteristic binding variables.

For the time being, it was decided only to perform the explicit entry of initial binding variables, because the entry of phenomena and determination of characteristic variables is a very extensive job. The number of different possible characteristic variables is much smaller than the number of possible phenomena (a multitude of different phenomena, for example, shock waves, sound, spreading of vibrations, etc., can be described with the same variables).

2.2.2. Relations and basic schematics

Relations are functional connections that are based on macroscopic material properties. They consist of physical variables x_i, material constants c_j (in general, these are treated as variables, which is exploited as an important design source), geometrical parameters g_k, and fundamental constants C_l:

$$y = f(x_i, c_j, g_k, C_l) \qquad (i, j, k, l) \in \{N\}$$

$$c_j = h(\ldots); g_k = p(\ldots) \tag{1}$$

Abstraction of relations between variables and constants (in this case without operators) is sufficient for chaining itself. Quantitative description (in this case, with operators) is indispensable for assessing suitability of relations (for example, assessing the order of magnitude of the changes and therefore their usefulness) and for analysis of the designed technical system.

Since physical laws are used in the conceptual design of technical systems, a question arises of how it is possible to perform design using physical laws when one knows that each technical system must also have components that materialize the physical laws used (Žavbi & Duhovnik, 1997). What is extremely important is that each relation includes certain basic topology, geometry, and the relevant environment (which is represented through material and fundamental constants), which can be said to represent a primitive technical system This can be illustrated with a basic schematic (Figure 5). Let us examine the following relation, for example:

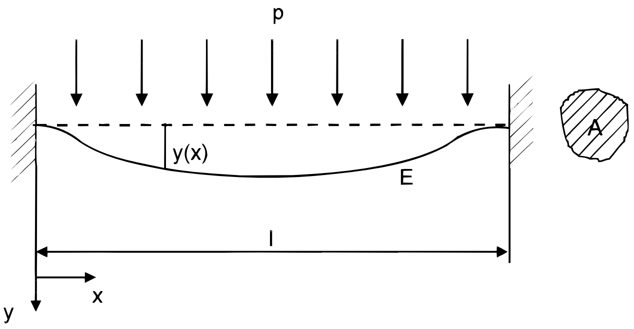


Fig. 5. Basic schematic complementary to relation (2).

$$y(x) = \frac{p}{24EI} x^2 (l - x)^2, \tag{2}$$

where

p = pressure (variable-cause)

E = Young's modulus

I = moment of inertia for element cross section

y = deflection (variable-effect), y coordinate

x = x coordinate

Its abstraction is: $y = f(p, x, l, E, I)$. An additional piece of information, which needs to be explicitly stated, is causality (what causes what; for example, pressure p (variable-cause) on a membrane causes its deflection y (variable-effect)).

Relation (2) is an equation for the deflection of a beam rigidly attached on both sides. It presents the quantitative connection between complementary variables, constants, and geometrical parameters. It can be seen that the equation is about an element with certain material and geometrical properties, an elastic element as defined by the Young modulus E, while the element's cross section defines the moment of inertia I, which hides the geometry of the cross section within it (that is, the shape of the cross section and its dimensions). It can be seen that already relatively simple relations conceal several sources for conceptual design of technical systems—in other words, new products (different cross-sectional shape, different dimensions, and different material fulfill the new requirements).

2.2.3. *Chaining*

Chaining of relations is necessary when a single relation cannot directly bind input and output variables of a technical system (Žavbi & Duhovnik, 1997). This is possible through chaining of relations.

As mentioned above, chaining is initiated with the initial binding variable which can identify appropriate relations (according to the algorithm), and these, in turn, represent the basis of the designed technical system. If a relation or relations fulfill the conditions stated in the algorithm, chaining can be completed. In the opposite case, chaining (and, therefore, the conceptual design chain) continues. The chain, which represents the entire conceptual design of a technical system, was named the conceptual design chain or partial chain, if it pertains to conceptual design of part of a technical system.

The course of designing and conceptual design consisting of relations and basic schematics can be presented with a simple schematic (based on the algorithm; Figure 6) in which the initial node root represents the initial binding variable, while other nodes represent other appropriate binding variables. The connections between nodes represent physical laws. Each of the generated paths in the graph presents a conceptual-design chain. The numbers of nodes designate the order of node generation.

In order to be able to use a generated conceptual design chain in the conceptual design of a technical system (or only part thereof), each physical law in the chain is presented with a complementary basic schematic.

The physical laws in the chain and the corresponding complementary basic schematics, therefore, actually represent the conceptual design of a technical system (Žavbi, 1998).

The method for generation of (partial) conceptual design chains leads to exploration as one method of solving problems, including ours. The problem of generation of conceptual design chains may be illustrated by exploration space, which represents relations, and solution space, which represents a (partial) chain in this space.

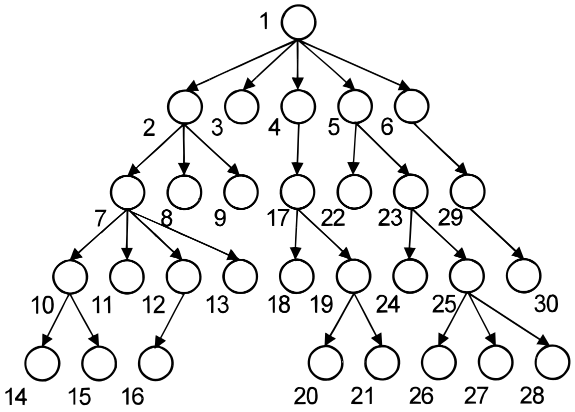


Fig. 6. Schematic of chaining.

In our case, the connections between nodes (relations) are not predetermined, but are generated dynamically, depending on binding variables. This is enabled by the algorithm that states that relations can be connected through binding variables.

The conceptual design of technical systems through the chaining of abstractions of physical laws is presented on examples of conceptual design of certain technical systems (see Examples).

3. EXAMPLES

3.1. Capacitor microphone

One of the characteristics of a pressure wave or explosion resulting from the interaction of laser with matter is also a variation in the *pressure* of surrounding air p. This variable is selected as a binding variable and used to search abstractions of physical laws or physical relations that contain such a variable and which are valid in this situation. Pressure p as the initial binding variable can identify the following abstraction:

$$d = f(p, D, r, r_m), \tag{3}$$

where

p = pressure (variable-cause)
d = deflection (variable-effect)
D = membrane's moment of resistance
r_m = membrane diameter
r = polar coordinate

with a quantitative equation:

$$d = \frac{p}{64D}(r_m^2 - r^2)^2,$$

that represents the deflection of a membrane (Figure 7), which is loaded transversely and uniformly and clamped rigidly. The relation introduces basic geometry (membrane with dimensions) and material (concealed in the membrane's moment of resistance) into the chain. According to the algorithm (see Section 2.1.), chaining can be completed, since

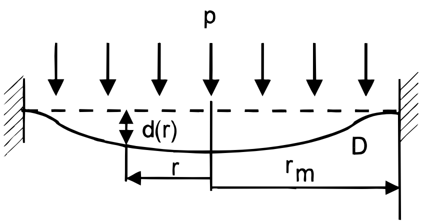


Fig. 7. Membrane deflection—basic schematic.

deflection d belongs to the set of geometrical variables. In this manner, a technical system was designed (with only one component, a membrane), which transforms *pressure p* into *deflection d*. Chaining will be continued, however, because we are interested in the effects of *deflection d*. The algorithm is used again, with *deflection d* as the initial binding variable, which also identifies the following abstraction:

$$C = f(d, A, K, \epsilon_0), \tag{4}$$

where

C = capacitance (variable-effect)
K = dielectric constant
ϵ_0 = permittivity of free space
A = characteristic area of capacitor plates
d = distance (variable-cause)

with a quantitative equation:

$$C = K\epsilon_0 \frac{A}{d}.$$

The above relation introduces a plate capacitor (Figure 8) and its basic geometry and material of the dielectric. The conceptual design of the technical system was augmented using a new component, a capacitor, and according to the algorithm chaining can be completed. But, since we would like to find out which relations can be identified by *capacitance C* and how the conceptual design can be expanded, the algorithm is used again with the capacitor's *capacitance C* as a new binding variable. This, among others, identifies the following abstraction:

$$U = f(C, R, U_0, e, t), \tag{5}$$

where

U = voltage (variable-effect)
U_0 = emf
e = exp = 2.7182...
t = time
R = resistance
C = capacitance (variable-cause)

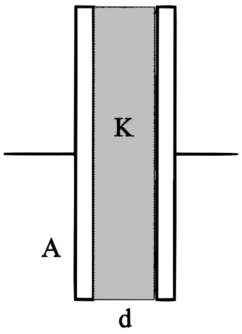


Fig. 8. Capacitance—basic schematic.

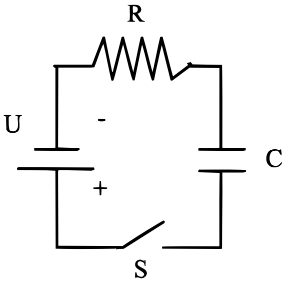


Fig. 9. Capacitor discharging—basic schematic.

with a quantitative equation:

$$U = U_0(1 - e^{-t/RC}),$$

which represents charging of a capacitor connected into a circuit according to the schematic in Figure 9. According to the algorithm, chaining must be continued, since neither *capacitance C* nor *voltage U* belong to the sets of base, geometrical, or material variables.

The new binding variable, *voltage U*, identifies, among other relations, the abstraction of *Ohm's law* (see also Figure 10):

$$I = f(U, R), \tag{6}$$

where

U = voltage (variable-cause)
R = resistance
I = electrical current (variable-effect)

with a quantitative equation: $U = RI$. Chaining according to the algorithm is completed because the binding variable, *electric current I*, is one of the base variables. A partial conceptual design chain is obtained (Figure 11). Qualitatively, the chain can be described as follows: the *pressure* of the shock wave affects the *deformation* of the elastic element, the mem-

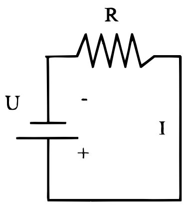


Fig. 10. Ohm's law—basic schematic.

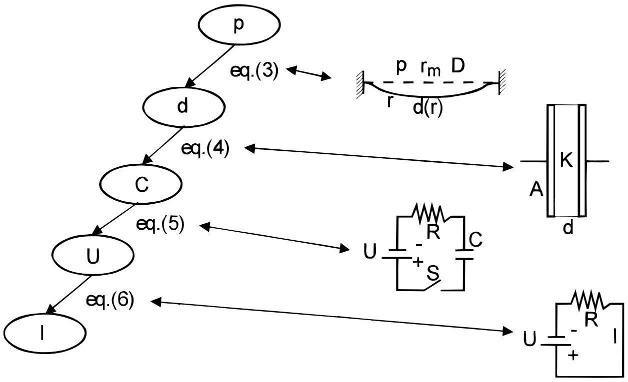


Fig. 11. Conceptual design chain for a capacitor microphone.

brane; this, in turn, affects *voltage* on the capacitor. Capacitor microphones operate on this principle (Figure 12).

At present, the transition from basic schematics (Figure 11, right side) to capacitor microphone schematics (Figure 8) must be performed by the user. Formalization of this transition is the next step that must be taken in the development of the conceptual design model. Special attention must be paid to the overlapping of functions—it can be seen in Figure 12 that the membrane functions simultaneously as one of the capacitor's plates.

3.2. Container

Let us imagine a container for rainwater in which the water level may not exceed a certain limit. *Water level h* in the container could be used as a suitable initial binding variable, and this is used to find the following abstraction (see also Figure 13):

$$p = f(h, g, \rho), \tag{7}$$

where

p = hydrostatic pressure (variable-effect)

ρ = density of fluid

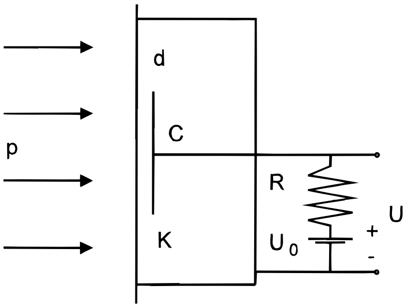


Fig. 12. Schematic of a capacitor microphone.

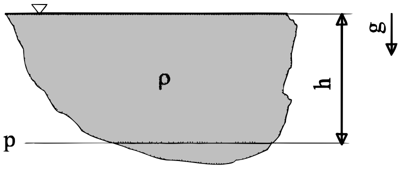


Fig. 13. Liquid in an open container—basic schematic.

g = acceleration of gravity

h = fluid level (variable-cause)

with a quantitative equation: $p = \rho g h$. According to the algorithm, chaining could now be completed since *fluid level h* belongs to the set of geometric variables. However, since we are interested in which relations can be identified by *pressure p*, the algorithm is used again with hydrostatic *pressure p* as the initial binding variable, with which the following abstraction, among others, can be identified (see also Figure 14):

$$F = f(p, A), \tag{8}$$

where

F = force (variable-effect)

p = pressure (variable-cause)

A = characteristic area

with a quantitative equation: $F = pA$. Chaining is now continued with the binding variable *force F*, because neither *force F* nor *pressure p* belong to the sets of base, geometrical, or material variables. This, among others, identifies the following relation (see also Figure 15):

$$F = f(x, k), \tag{9}$$

where

F = force (variable-cause)

k = spring constant

x = displacement (variable-effect)

with a quantitative equation: $F = -kx$. With this relation, chaining can be completed, because *displacement x* be-

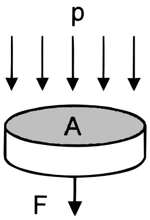


Fig. 14. Definition of pressure—basic schematic.

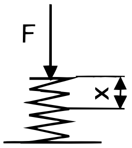


Fig. 15. Spring—basic schematic.

longs to the set of geometrical variables; the technical system represented by the chain (Figure 16) is shown in Figure 17.

The conceptual design chain can be described qualitatively as follows: the *fluid level* affects *hydrostatic pressure*, and, this in turn, affects spring *displacement*, which enables the outflow of excessive amounts of water.

3.3. Summary of presentation of the conceptual design model with examples

This section presents two examples of reconstructed conceptual design of existing technical systems (a condenser microphone), and conceptual design of a physically possible technical system (a container).

The used physical laws are summarized from various textbooks of university physics (Schubert, 1982; Shive & Weber, 1984; Kladnik, 1985; Giancoli, 1988, 1998).

The mathematical equations used in the examples are quantitative, but it must be emphasised that, for conceptual design itself, only participating physical variables, material constants, geometrical parameters, and fundamental constants are necessary and are sufficient. Such method of writing physical laws is useful for a prototype of computer-aided conceptual design.

In the examples presented, physical laws are accompanied by basic schematics, that is, primitive technical systems that are the basis for the designed technical systems. Only those conceptual design chains (i.e., generated paths) are stated that are actually used in technical systems reconstructed according to the algorithm.

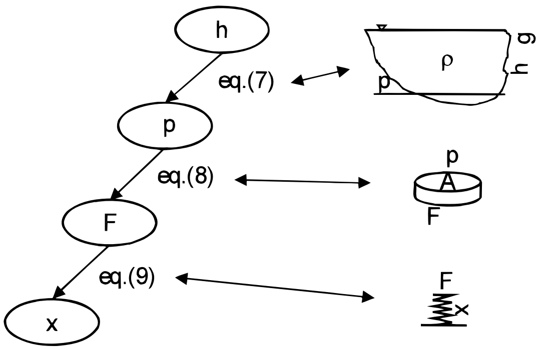


Fig. 16. Conceptual chain of container.

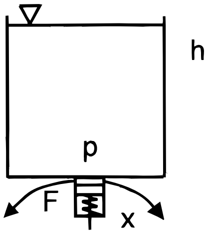


Fig. 17. Schematic of container.

4. IMPLEMENTATION OF A COMPUTER-AIDED SYSTEM FOR THE CONCEPTUAL DESIGN OF TECHNICAL SYSTEMS BASED ON PHYSICAL LAWS

This section presents an implementation of a computer-aided system for conceptual design based on physical laws. Primarily, the writing of relations and the results of use of the prototype will be presented. The advantage of a computerized version of a conceptual design model lies mainly in the speeds of chaining and accessing available relations which will be recorded in the relation database (the prototype contains only a few relations, simply to illustrate the functioning of the algorithm and the results obtained with its use). Chaining itself is not difficult; it can be performed equally well by hand.

The conceptual design method according to the algorithm and a schematic presentation of how the conceptual design chain is created immediately lead us to the use of trees in the presentation of the search space, and searching as a method for the creation of conceptual design chains. If the AHP method is not used (e.g., when searching for all appropriate conceptual design chains and not only the most appropriate ones), this is a blind search. If the AHP method is used to evaluate the functional suitability of relations, the search method is heuristic (the domain-specific information is acquired by mutual pairwise comparisons of the appropriate physical laws with respect to design requirements, which is one of the characteristics of the AHP method) (Žavbi & Duhovnik, 1996, 1998). It is, however, true that the user will also intervene, since the AHP method requires the designer's participation. The search space can be generated dynamically; physical laws are present and (according to the algorithm) the rules for their binding into a conceptual design chain are available. The solution is the generated conceptual design chain of a technical system.

We used the PROLOG computer language, which was also employed to make our first model of conceptual design in 1992 (Bratko, 1991; Duhovnik & Žavbi, 1992; Žavbi & Duhovnik, 1995, 2000). Many predicates are taken from Filipič (1988). One reason for its selection is simple manipulation with symbols, which is characteristic of the realized design model. We could also have used another language, because the coding of the algorithm is not difficult.

4.1. Writing relations

This subsection first presents a general way of writing relations that form one of the crucial parts of the conceptual design model. Concrete relations that were used in our examples are also recorded.

Let us now briefly repeat what a record of relations must include: in general, a record of physical variables, material constants, geometrical parameters, and fundamental constants that define a physical law (and here our concept of a physical law should not be forgotten). The record must also include information about whether an individual variable is a cause or an effect. Since it was planned in the algorithm that chaining can be completed when the first or the second or both variables in the current relation belong to the sets of geometrical, material, or base variables, the record must also contain this information.

4.1.1. *General record with an example*

The description of relations is performed using attribute vectors—a formalism that was already used in creating the first model.

```
/*
attr_vector(
            Physical_law,
            [
            [Parameter_1, Index_1, Index_2, Status],
            [Parameter_2, Index_1, Index_2, Status],
            [Parameter_n, Index_1, Index_2, Status],
            ...
            ],
            Appendix1, Appendix2).
*/
```

`Parameter_n` represents the names of variables, for example, pressure, temperature, force, etc. `Index_1` and `Index_2` can be designated `no` (cause-independent), `od` (effect-dependent) or `irel` (when causality is not relevant). According to their status, `Status`, variables can be designated as `known` or `unknown`, depending on whether they are geometrical, material, base variables, constants, or variables. The addition, `Appendix1`, currently contains the pointer to the basic schematics and, `Appendix2`, quantitative recording of a relation.

Let us examine the form of a relation for the amount of heat input necessary to heat a material:

$$Q = mC\Delta T, \tag{10}$$

where

Q = heat (variable-cause)

m = mass of element

C = specific heat

ΔT = change in temperature (variable-effect)

```
attr_vector(
           specific_heat,
           [
           [heat, no, no, unknown],
           [change_temperature, od, od, known],
           [mass, irel, irel, known],
           [specific_heat, irel, irel, known]
           ],
           [schematics_spec_heat, ′Q=m*C*DT′]).
```

In the above relation, heat, and change in temperature, change_temperature, are treated as cause-no and effect-od. Temperature, as the base variable, is known, as is mass. Specific_heat is a material property and the status of its knowledge is known.

4.2. Chaining

The coding of an algorithm (see Section 2.1.) is straightforward and the code itself contains no optimization tricks. Let us, therefore, examine a few results obtained with the prototype.

The database of physical laws contains 30 physical laws. The figures below show what and how many conceptual design chains can be generated using the prototype for temperature T, pressure p, and voltage U as the input variables (Figures 18–25).

It should be emphasized that the above results were obtained without the use of the AHP method, because we

```
---------------------------------------------------------------
              File: temp.dat
          Variable:
                Input (root node): temperature
                             Type: cause
               Output (leaf node): any
Type of generation: all solutions
      Results-form:
No.  No. of physical laws     Chain     Output variable
---------------------------------------------------------------
1: (1) -> spec_resistance (sp_resistance)
2: (1) -> heat_expansion (length)
---------------------------------------------------------------
No. of chains: 2
```

Fig. 18. An example of generated chains for *temperature T-cause* as an input variable generated by the prototype.

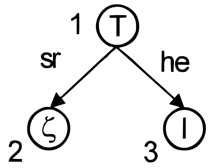


Fig. 19. Illustration of conceptual design chains for *temperature T*-cause as the input variable. 1–3: generation of nodes; sr—*spec_resistance*, he—*heat expansion*.

wanted to generate all of the appropriate (i.e., all those which can transform an input variable into an output variable) conceptual design chains for technical systems (from a database of 30 physical laws) and not only the most appropriate ones. The most appropriate conceptual design chains are those which are assessed as such with the AHP method, with respect to the design criteria.

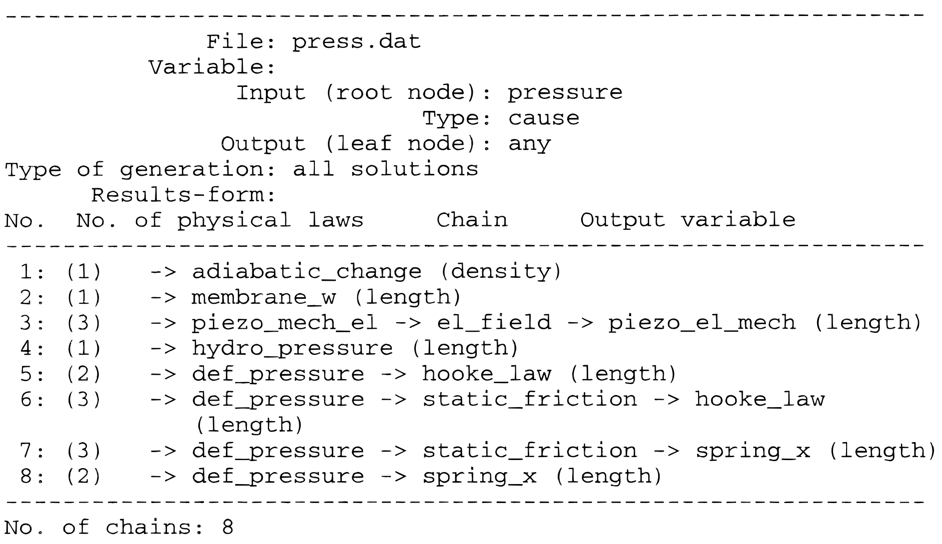
4.3. Evaluation of the prototype of computer-aided conceptual design of technical systems

This prototype's purpose is to show results of algorithm use (Figures 18–25) and an example of writing physical laws. It is one of several possible ways of recording relations. It is not our current intention to produce software that would optimally use processor time and memory and be immediately commercially applicable.

The prototype does not present a quantitative record of physical laws, since it has been pointed out several times that this is not a required condition for chaining itself, nor for the conceptual design of technical systems.

The method used belongs to the group of search methods. The solutions (i.e., conceptual design chains) are paths in the tree; if the AHP method is used, the solution is one path in the tree. Since the AHP method is used to continue chaining by determining the most appropriate successor (in this case a physical law), it can be grouped among heuristic search methods. It is emphasised here that our method always finds a solution, if it exists, since it could happen that the chain cannot yet be completed according to the algorithm, but the search space would offer no available relation that would fit the last binding variable. The method belongs to the group of deterministic methods, since identical results are obtained for the same input data. This is obvious, since, for example, a random number generator is not used anywhere in the process. The method is also satisficing, because it always finds a good solution (Figures 24 and 25), which is achieved by local use of the AHP method (meaning that only last relations in a chain are compared and not the entire set of relations in a chain). If the AHP method is excluded, it can be said that this method is exhaustive, because it visits the entire search space (30 physical laws in the prototype); such method finds all possible solutions (Figures 18–23). Each method which is exhaustive is also complete (Stefik, 1995).

The used method is monotone in the decision space (i.e., the multitude of appropriate physical laws that are identified by the binding variable; which of them is selected to continue chaining is determined with the AHP method), because revising a decision is not performed. After a relation which will be used to continue chaining is selected, one can no longer change this decision and continue chaining with a new relation. However, experience has shown that use of the AHP method in assessing the appropriateness of rela-



```
--------------------------------------------------------------
              File: press.dat
          Variable:
                Input (root node): pressure
                             Type: cause
               Output (leaf node): any
Type of generation: all solutions
      Results-form:
No.  No. of physical laws     Chain     Output variable
--------------------------------------------------------------
 1: (1)   -> adiabatic_change (density)
 2: (1)   -> membrane_w (length)
 3: (3)   -> piezo_mech_el -> el_field -> piezo_el_mech (length)
 4: (1)   -> hydro_pressure (length)
 5: (2)   -> def_pressure -> hooke_law (length)
 6: (3)   -> def_pressure -> static_friction -> hooke_law
             (length)
 7: (3)   -> def_pressure -> static_friction -> spring_x (length)
 8: (2)   -> def_pressure -> spring_x (length)
--------------------------------------------------------------
No. of chains: 8
```

Fig. 20. An example of generated chains for *pressure p*-cause as an input variable generated by the prototype.

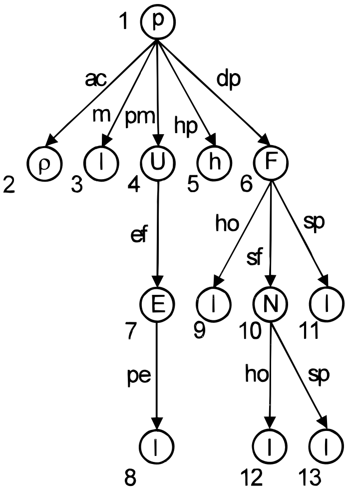


Fig. 21. Illustration of conceptual design chains for *pressure p*-cause as the input variable. 1–13: generation of nodes; p—*pressure*, *ρ*—*density*, l—*length*, U—*voltage*, h—*height*, F—*force*, E—*electric field*, N—*normal force*; ac—*adiabatic_change*, m—*membrane_w*, pm—*piezo_mech_el*, ef—*el_field*, pe—*piezo_el_mech*, hp—*hydro_pressure*, dp—*def_pressure*, ho—*hooke_law*, sf—*static_friction*, sp—*spring*.

tions is sufficiently good for the selected relations in the conceptual design chain to fulfil the design requirements expressed by the design engineer, by determining the criteria for selection and by pairwise comparisons of criteria and appropriate relations with regard to individual criteria.

5. CONCLUSION

The model based on the algorithm as such is subject to the constant risk of rejection if it fails to reconstruct an existing technical system. Such a case was not encountered during testing of the model. It must again be emphasized that this refers to conceptual design that uses physical laws as a source.

According to the algorithm, a quantitative record of physical laws is not required for conceptual design, because the participating physical variables, material and geometrical parameters, and fundamental constants suffice—abstractions of physical laws suffice. The potential for an expansion of the basic source of conceptual design is also hidden in material constants (for example, the discovery and description of piezo effect opened new possibilities in conceptual design), since they themselves can also depend on physical variables. The same applies to various approximations or idealizations. In the future, the study of these facts could strongly increase the basic source of conceptual design of new technical systems. In the presented conceptual design model, this source is accessible. Simultaneous treatment of different sources of conceptual design described with relations makes possible a greater availability of relations useful for designing, and, therefore, a greater number of innovative combinations achieved through chaining.

The above information should also be transferred into software to exploit advantages of our approach. In producing computer-aided conceptual design tools based on physical laws, special attention must be paid to symbols for variables that appear in relations, because different designations for the same variables prevent their accessibility.

In the future, it will probably be necessary to find a suitable method for the extraction of initial binding variables from the functions of technical systems we desire to design. A poor selection of the initial binding variable could cause an inability to design a technically feasible system, which would become evident during the evaluation of the appropriateness of the corresponding physical laws. Currently, those initial binding variables are used that the design engineer believes to be characteristic for the function of the future technical system.

The idea of causality is used beneficially in the supplement to the algorithm, namely in the description of relations and chaining itself. Intuitively, one feels that such a qualitative causal explanation of relations is appropriate. However, from the viewpoint of theory of science, one cannot speak of true causality in the case of functional interdependence of several variables. This is because it is not a

```
----------------------------------------------------------------
              File: volt.dat
          Variable:
                Input (root node): voltage
                             Type: cause
               Output (leaf node): any
Type of generation: all solutions
      Results-form:
No.  No. of physical laws     Chain     Output variable
----------------------------------------------------------------
1: (2)     -> el_field -> piezo_el_meh (length)
----------------------------------------------------------------
No. of chains: 1
```

Fig. 22. An example of a generated chain for *voltage U-cause* as an input variable generated by the prototype.

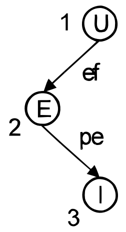


Fig. 23. Illustration of conceptual design chains for *voltage U*-cause as the input variable. 1–3: *generation of nodes*; U—*voltage*, E—*electric field*, l—*length*; ef—*el_field*, pe—*piezo_el_mech*.

case of their succession in time; rather, it is that of parallelism (Ule, 1992). For example, for relation $pV =$ constant one cannot say that a change in volume is the cause (consequence) of a change in pressure (Ule, 1992). If the idea of causality was not used, it would be possible to design technical systems that could not be interpreted correctly. These would constitute a subgroup of the multitude of all designed technical systems.

Our initial experience has shown that the selection of initial binding variables, the size of the set of physical laws, and assigning of causality to individual variables are of crucial importance for the applicability of the conceptual design model. In addition, the correct designation of physical variables, material constants, and geometrical variables of the same type is essential to the operation of a computer-aided conceptual design tool.

At present, the transition from the basic schematics (e.g., for a capacitor microphone, Figures 7, 8, 9, and 10) to a schematic of a technical system (e.g., for a capacitor microphone, Figure 12) is done by the user. The formalization of the transition is the next step in the development of a conceptual design model, as is the use of formalization in generating detailed geometry and topology.

Relations, therefore, contain all the conceptual design sources for new products or their improvements. It must be emphasized that this refers to the sources of technical improvement, which is not necessarily interesting for the market.

The essential material contribution of the presented model is the use of known physical laws and not only those that are materialized through the available components of individual domains. This undoubtedly increases the possibilities for the conceptual design of innovative technical systems, since in the extreme case it is possible to design a technical system that will require first the development of all its components (the basic schematics are given by the model) to the last detail, and then the design of the manufacturing technology for them and their manufacture.

If physical laws extracted from already existing components are used, innovations are limited to only various combinations of the existing components. A further shortcoming is the problem of extracting physical laws that are materialized in the available components: for example, in a polished metal pipe the law of continuity (which is “standard” for a pipe) is materialized, but so are Ohm’s law, the law of heat conductivity, the law of reflection, etc., which are not obvious at first glance. Each physical law that is not extracted from an individual component thus limits the possibilities of designing innovative technical systems. The available components also do not include “natural” ones, such as, for example, a drop of liquid, fluid level, air compression, light beam, etc., which additionally limits the conceptual design of innovative technical systems.

In brief: the essential advantage of our model originates from the use of known physical laws (in fact their abstractions) and complementary basic schematics (these represent the schematics of components), in which individual physical laws are materialized. In this manner, the basic schematics include “natural,” technologically available and also unavailable components.

What is the value of the model presented for designers of technical systems? It guides them directly into the use of physical laws, relieving them from considering adaptations of the existing solutions or composition of solutions from the existing components. In addition, it provides focused access to one of the sources of conceptual design (including innovations derived from physical laws), because design engineers meet “new” physical laws, and through chaining they can discover new combinations of laws already known

```
----------------------------------------------------------------
              File: press_ahp.dat
          Variable:
                Input (root node): pressure
                             Type: cause
               Output (leaf node): any
Type of generation: AHP use
      Results-form:
No.  No. of physical laws     Chain     Output variable
----------------------------------------------------------------
 7: (3)   -> def_pressure -> static_friction -> spring_x (length)
----------------------------------------------------------------
```

Fig. 24. An example of generated chain for *pressure p-cause* as an input variable generated by the prototype (obtained with the use of the AHP method).

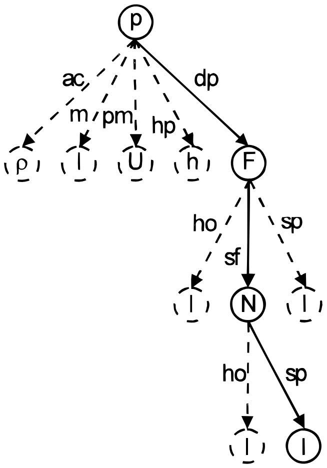


Fig. 25. Illustration of a conceptual design chain for *pressure p*—cause as the input variable (obtained with the use of the AHP method). p—*pressure*, *ρ*—*density*, l—*length*, U—*voltage*, h—*height*, F—*force*, N—*normal force*; ac—*adiabatic_change*, m—*membrane_w*, pm—*piezo_mech_el*, hp—*hydro_pressure*, dp—*def_pressure*, ho—*hooke_law*, sf—*static_friction*, sp—*spring*.

to them. The method also enables adaptations of the existing physical laws to fulfil new functions, represented by initial binding variables.

Another essential aid to conceptual design are the basic schematics complementary to physical laws, in which individual physical laws are materialized. This is because a result of the conceptual design phase is a schematicized presentation of a future technical system (Duhovnik, 1987; Pugh, 1991, Ullman 1992) with corresponding physical laws.

ACKNOWLEDGMENTS

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