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APPLICATION OF WIRK ELEMENTS FOR ELEMENTARY EMBODIMENTS OF TECHNICAL SYSTEMS

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ABSTRACT
The paper presents a method of graphical embodiment of abstract conceptual solutions which were automatically generated by chaining of physical laws. For this purpose, a repository of 125 physical laws was generated, where each law is also presented graphically as a basic schema composed out of maximum four graphical elements with the ability to be freely shaped. This tool enables application of physical laws for the analysis of existing technical systems and also for synthesis of new ones. Procedure of formalising the transition from physical laws to a schema of a future technical system is indicated. Physical laws are used to conceptualize or upgrade existing technical systems where the main focus is on their synthesis.

Keywords: part synthesis, physical law, basic schemata, wirk element

1 INTRODUCTION
Many tools to support activities in conceptual phase have been developed for the purposes of generating conceptual solutions, but only a few support their graphical embodiment. The methods, most frequently used for generating concepts, such as brain storming and brain writing are very simple to use but their success depends much on the experience and also on representational abilities of the users. Competitors' products or similar products as well as analogies from the nature are also an important source of ideas. Using catalogues of solution principles or function-component matrices [1], [2], [3], [4] is an efficient way to systematically extract design knowledge from existing products and apply it to new conceptual solutions.
It is not necessary to change all principles in the technical system to get an alternative solution; it is often enough to change only one. But on the other hand, not all principles are compatible with each other. So it is suggested by Roth [2] to make abstract definition of the technical system first. Its concrete alternatives are sought later. Work on a more abstract level supports new knowledge about the problem and significantly increases chances for a success [5]. The most straightforward way to abstract definition of technical system is to describe its functionality by physical laws. Basis for such an approach is given in the literature [2], where matrix of functional quantities is a two-dimensional field, with dependable physical variables on the ordinate axis and independent physical variables on the abscissa axis. Connection between the ordinate and the abscissa variables is established through physical laws. If a law includes both variables, the connection is possible, otherwise not. The connecting physical laws are gathered in the design catalogue. This way, we are able to search for all possible solutions (quantities) to a specific input variable (quantity). If the output (independent) variable is again selected as an input (dependable) variable we get a chain of physical laws that eventually should bring us to the desired output.
Further development of this method brought automated, computer generation and optimization of concepts. These tools already provide textual, bond graphs or symbolic descriptions [6],[7],[8] and in some cases also graphical presentation of conceptual solutions [9]. The problem which arises is embodiment of the abstract conceptual solution. In the conceptual shape design, the variety of shape

concepts is at least as large as the variety of the design concepts [10]. Several tools have been developed for different research fields with different requirements and purposes of design. Conceptual design chains of physical laws where basic schemata were first used showed problems in transition from basic schemata to a schema of a conceptual technical system [11],[12]. To enable transition, more formal description of basic schemata was needed. It was noted that transition could be performed formally via decomposition of basic schemata into a set of graphical elements where functions are being realized [17]. In mechanical design literature, geometrical elements where functions are being realized have different names: wirk elements [1], [2], [13], [14], function carriers [15], [16] and effective elements or spaces [9], [16]. When using physical laws for concept generation in the embodiment phase (as indicated in [17]), geometrical elements where function is being realized are point, line, surface and volume. Out of the latter three elements (point is integrated into wirk element of higher complexity such as line or surface due to non dimensionality), basic schemata were build for a repository of 125 physical laws. In the follow-up, their usability in embodiment phase of the conceptual design will be shown.

Functions can be realized with the usage of at least one physical law but mainly a chain of several laws is needed, moreover some functions can be fulfilled in several different ways. This can be observed on products that fulfil the same function but with different working principles (for example: wire bulbs and neon bulbs). Supposing that the lowest level function is realized by only one physical law and that a chain of laws or even different chains of laws can act on the same wirk element, then these functions share a wirk element.

Ulrich defined function sharing as a simultaneous implementation of several functions by a single structural element [6]. With function sharing we reduce the number of needed parts, we optimize the shape of TS and these designs are most often more efficient. This is strongly supported when using a chain of basic schemata. Ulrich's procedure to achieve function sharing consists of three steps. Firstly, a structural element is deleted from the physical description, secondly, we search for alternative features in the physical description that can potentially implement the function of the deleted element and thirdly, identified features are modified to accentuate their desirable secondary properties. He also identifies functional sharing on physical, component and feature level.

Structure sharing means fulfilment of several functions or functional properties by the same physical structure [18]. Although structure sharing can also have a negative impact of decreasing its changeability, several authors [6], [11], [18] stress that structure sharing usually leads to a better design. Basic schemata represent the working principle of the future TS and are combined on the conceptual level. Basic schemata approach can be used for adaptive optimization as well as to generate different variants. It is also noticeable from the basic schemata whether some working principles could be fulfilled on the same structure.

2 BASIC SCHEMATA

Henceforth, we will limit the procedure of building basic schemata to the macro world where deterministic physical laws are valid. Basic schemata were thus generated for the repository of 125 physical laws from mechanics, hydromechanics, optics, heat and electrics areas. Each physical law is represented by only one basic schema which may be realized in the form of many different embodiments at the end of concretization process. Basic schemata are further decomposed into one or several wirk elements (Figure 1).

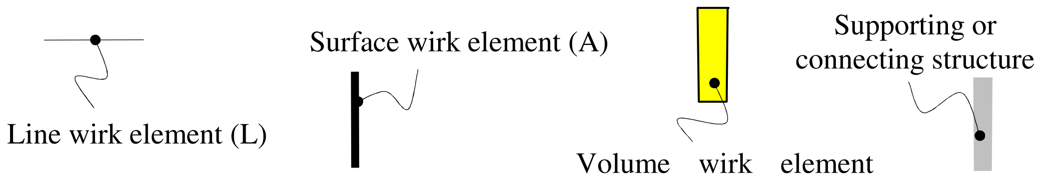
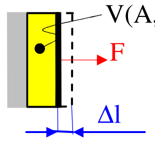
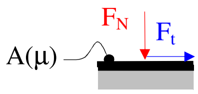
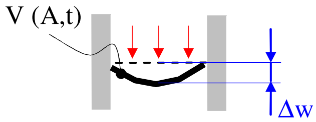
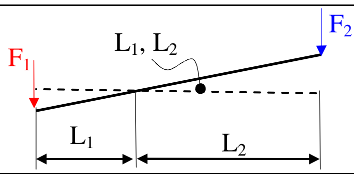
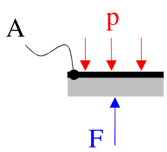
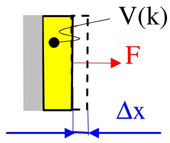
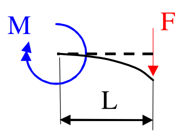


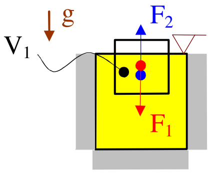
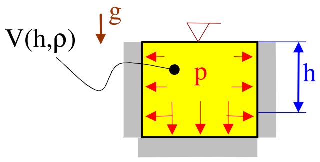
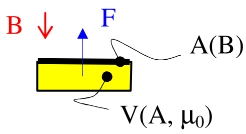
Figure 1. Geometrical building blocks of basic schemata.

Cases of identifying wirk elements and reasoning are known from the literature [17]. Decomposition of basic schemata into wirk elements enables flexibility to shape and optimize graphical schemata of

technical system, where also informal knowledge and experiences of the design engineer are applied. Analysing 125 physical laws, we identified 271 wirk elements where 49% of them were volume wirk elements, 37% were surface wirk elements and 14% line wirk elements.
In all basic schemata, there are also input and output variables, indicated with blue and red colour, for the purpose of a better clarity. The input variable (blue colour) is the output variable from the previous law, meanwhile the output variable (red colour) is a potential input variable for the following physical law in the chain. If two following laws are applied to the same wirk element, the input variable has the same direction as the output variable of the previous law, otherwise the direction is opposite.
Products or technical systems consist not only of geometrical places where functions are being realized but also of a structure that supports and connects individual wirk elements. Supporting or connecting structures are indicated in grey colour. Supporting or connecting structures can be made of the same materials as wirk elements or of a different material e.g. less expensive, since it does not contribute to the realization of the function directly. Clear identification of the effective volumes can lead to more optimized designs in the sense of the materials as well as in the way the loads are being transmitted through the structure.
Using physical laws for the purpose of designing, properties of the environment must be defined, too. In most cases, material properties define volume wirk element but gravitational, electric or magnetic fields are not integrated into wirk elements and must be defined separately.
Physical laws and corresponding basic schemata used in the article are presented in Table 1.

Table 1. Physical laws and corresponding basic schemata.

Physical law	Symbolic notation	Basic schemata	effect	Wirk elements
Hook law	$\frac{\Delta l}{L} = \frac{F}{AE}$		**F**, **Δl**	V
Static friction	$F \leq F_N \mu$		**F_N**, **F_t**	A
Membrane flexion law	$\Delta w = \frac{p}{64D}\left(r_m^2 - r^2\right)^2$		**p**, **Δw**	V
Lever law-force	$F_1 = F_2 \frac{L_2}{L_1}$		**F_1**, **F_2**	L_1, L_2
Static pressure law	$F = pA$		**p**, **F**	A
Spring law	$F = k\Delta x$		F, Δx	V
Torsion	$M_t = FL$		F, M_t	L

Buoyancy law	$F = \rho_2 g V_1$		F_1, F_2	V
Hydrostatic pressure	$p = \rho g h$		p, h	V
Magnetic force	$F = \dfrac{AB^2}{2\mu_0}$		**B, F**	A, V

One necessary property that is required from basic schemata is flexibility. All building blocks of basic schemata are composed from splines and thus enable flexibility when designing a new technical system.

3 CONCEPTUAL CHAIN OF BASIC SCHEMATA

To validate usefulness of basic schemata in conceptual design phase three main tasks should be fulfilled:

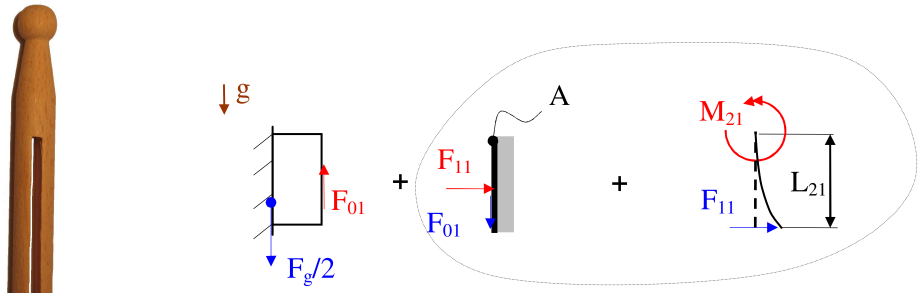
1. It should be possible to do reconstruction of an existing technical system;
2. It should be possible to generate alternative concepts;
3. It should be possible to evaluate feasibility of the generated concept.

The functionality of existing technical systems can be experimentally tested whereas the functionality of the generated alternative concepts needs to be evaluated which can be done by using physical laws. To show the procedure of using basic schemata, we used a rather simple product such as a cloth peg. The reason for this is that it is very difficult to find a complex product that works on the basis of one or on the basis of a sequence of only a few physical laws. In the cloth peg, we have a sequence of minimum two physical laws. When testing the method on more complex products, several chains of physical laws connect into a net of physical laws. Design engineer then focuses on one chain or part of the chain of physical laws. When searching the local optimum of the selected sequence of physical laws we should also check compatibility with the connecting chains. Doing this, we should also determine the operational boundaries. The procedure shows a sequence of physical laws which describe different variants of the cloth peg from Figure 2. The same method will be used to generate alternative conceptual solutions that use different physical laws to fulfil the desired function.

Figure 2. Different existing variants of the cloth peg.

3.1 Reconstruction of existing technical system

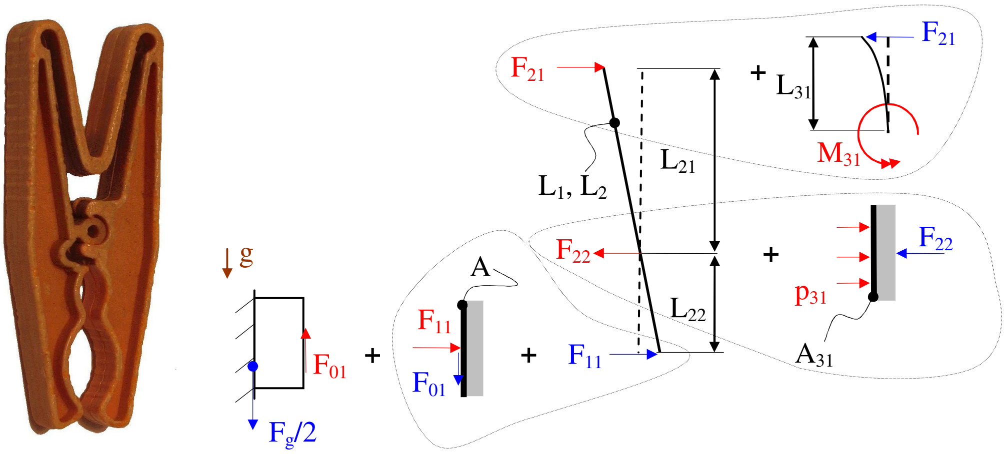
In the reconstruction phase, we will focus on the static state where clothes have been hanged. During hanging and unhanging, effects of some other physical laws could occur and thus the chain of laws that describe such state would be different and should be analyzed separately. Effect between the clothesline and the cloth peg are not included in the analysis. The study included several variants of cloth peg where function is realized by different physical laws.



$$\frac{F_g}{2} = F_{01} \longrightarrow F_{01} = F_{11}\mu \longrightarrow F_{11} = \frac{M_{21}}{L_{21}}$$

Figure 3. Basic schemata of the chain of physical laws which describe a wooden cloth peg made from one part.

Friction force (F_{01}) in Figure 3 equals one half of the gravity force of clothes ($F_g/2$). Normal force (F_{11}) causes momentum (M_{21}) which is the biggest where both clamp sides of the cloth peg merge.

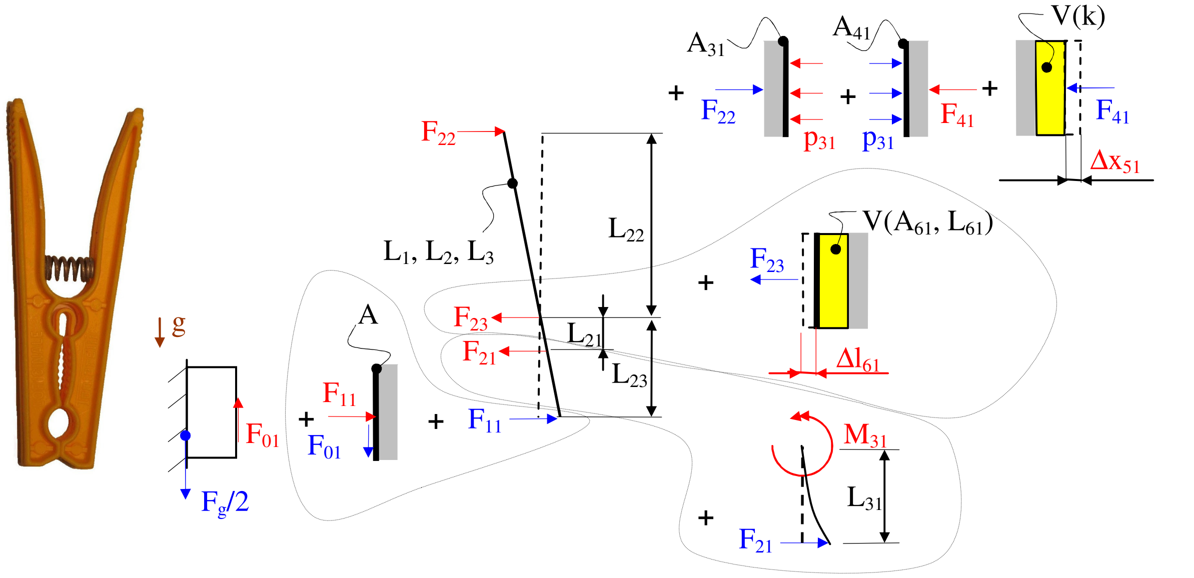


$$\frac{F_g}{2} = F_{01} \longrightarrow F_{01} = F_{11}\mu \longrightarrow F_{11} = F_{21}\frac{L_{21}}{L_{22}} \longrightarrow F_{21} = M_{31}L_{31}$$

$$F_{22} = F_{11} + F_{21} \longrightarrow F_{22} = p_{31}A_{31}$$

Figure 4. Basic schemata of the chain of physical laws of a plastic cloth peg made from one part.

Cloth peg from the Figure 4 is also made from one part. Here, the friction force (F_{01}) equals one half of the gravity force of the clothes ($F_g/2$). Optionally, part of the load can be transmitted through the surface pressure due to the shape of the clamp surface of the cloth peg. However, this effect is not included in the analysis of the cloth peg, because it might appear or it might not, which depends on the clothes. Such design is better from a functional point of view, because load transfer is available through two different effects, where the second effect does not reduce functionality of the first effect. Friction force is caused by a normal force (F_{11}), which causes bending stress on the handle side of the cloth peg as a result of the lever law (F_{21}) and the momentum law (M_{31}). Movement of both clamp sides away from each other is prevented by the sliding contact where reaction force (F_{22}) causes surface pressure (p_{31}) and tension stress in the outer part of the movable joint.



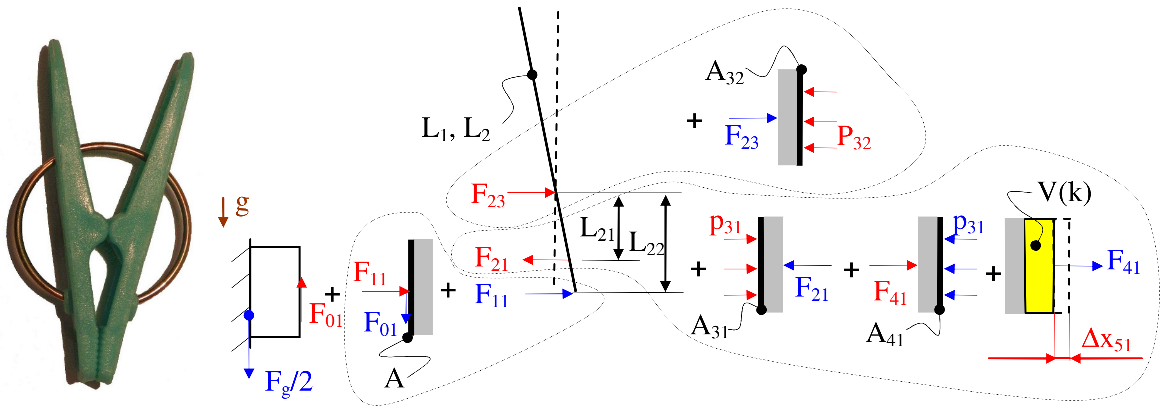
$$\frac{F_g}{2} = F_{01} \rightarrow F_{01} = F_{11}\mu \rightarrow F_{11} = \frac{1}{L_{23}}\left(F_{21}L_{21} + F_{22}L_{22}\right) \rightarrow F_{21} = M_{31}L_{31}$$

$$\rightarrow F_{22} = p_{31}A_{31} \rightarrow p_{31} = \frac{F_{41}}{A_{41}} \rightarrow F_{41} = k\Delta x_{51}$$

$$F_{23} = F_{11} + F_{21} + F_{22} \rightarrow F_{23} = EA_{61}\frac{\Delta l_{61}}{L_{61}}$$

Figure 5. Basic schemata of the chain of physical laws of a plastic cloth peg made out of two parts.

The cloth peg from Figure 5 consists of two parts. Load can be transmitted to the cloth peg by the friction (F_{01}) and pressure forces. However, consequences are also divided between the momentum stress due to the momentum law (M_{31}) and pressure stress (p_{31}) as a result of surface pressure, caused by the spring force (F_{41}). Here, functionality is achieved by two different parallel effects. The reaction force (F_{23}) causes tension stress in the fixed joint, defined by the Hook law.



$$\frac{F_g}{2} = F_{01} \rightarrow F_{01} = F_{11}\mu \rightarrow F_{11} = F_{21}\frac{L_{21}}{L_{22}} \rightarrow F_{21} = p_{31}A_{31} \rightarrow p_{31} = F_{41}A_{41} \rightarrow F_{41} = k\Delta x_{51}$$

$$F_{23} = F_{11} + F_{21} \rightarrow F_{23} = p_{32}A_{32}$$

Figure 6. Basic schemata of the chain of physical laws of a plastic cloth peg made out of three parts.

In the case of the cloth peg from Figure 6, functionality is fulfilled by a spring. Both the normal force (F_{11}), causing the friction force (F_{01}), and the spring force (F_{41}) act on the same side of the lever. Such configuration causes surface pressure (p_{32}) in the area where both sides of the cloth peg are joined together.

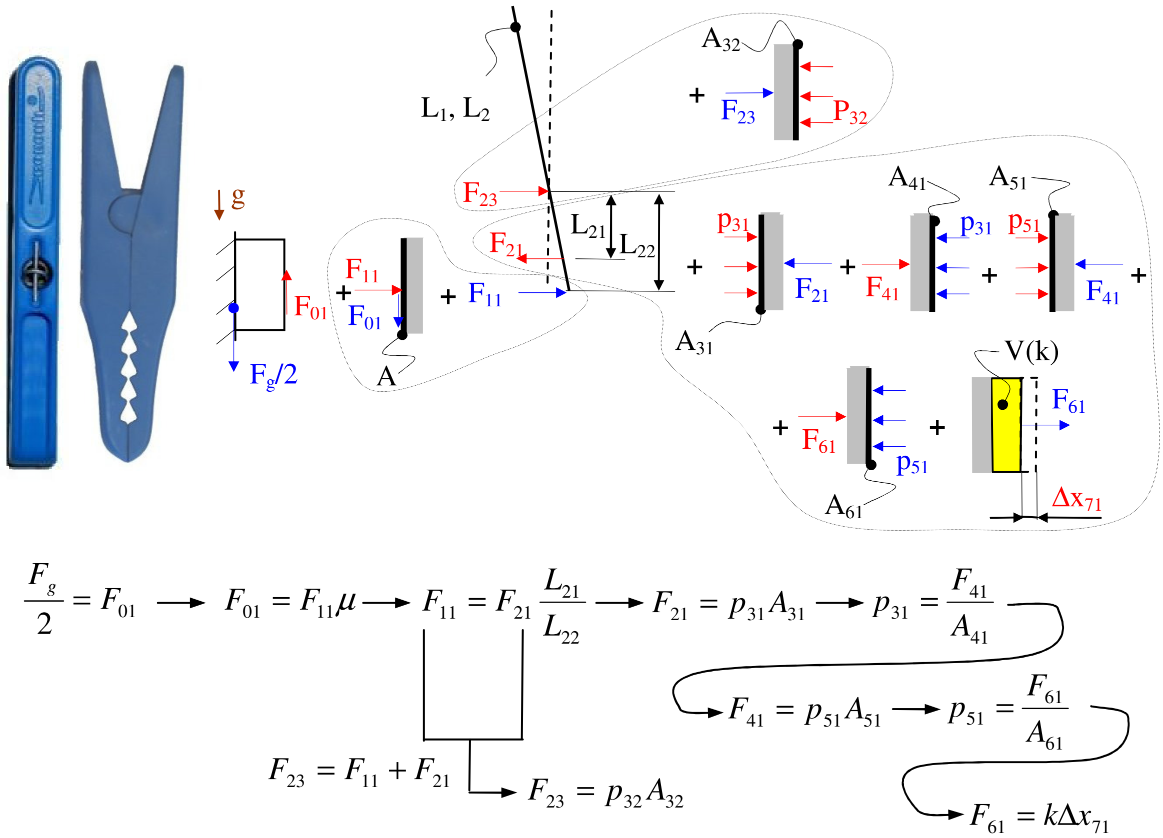


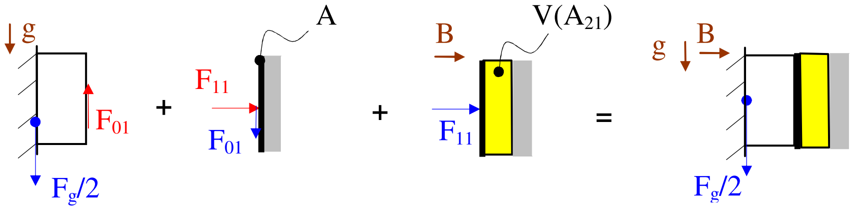
Figure 7. Basic schemata of the chain of physical laws of a plastic cloth peg made out of five parts.

Although the cloth peg from Figure 7 uses the same working principle as the cloth peg from Figure 6, several other laws are required for its description because this cloth peg is composed out of five parts and effects are transmitted from one part to another with the application of at least one physical law. The normal force (F_{11}) is transmitted to the spring (F_{61}) over a small steel rod. Force from the clamp (F_{21}) causes pressure (p_{31}) on the steel rod on the contact area between the clamp and the steel rod. Steel rod causes further pressure on the spring hook (p_{51}).

3.2 Concept generation and its synthesis

In the chapter, reconstruction of the existing technical system basic schemata were used for the analysis. We will now use the same basic schemata for the purpose of concept generation and synthesis of technical systems that fulfil the same function as the cloth peg. For the purpose of concept generation, we used the gravity force as the starting variable of the solution chain of physical laws, which was similar to the presented cloth pegs. We limited the length of the solution chain to a maximum of four physical laws without possibility to repeat any law that has already been included in the chain. From the basis of 125 physical laws, we got a set of 268 chains that fulfil the requirements described above. There were 69 chains where the friction law was the first physical law in the solution chain. Number and outcome the of solution chains depends on the chaining algorithm. The chaining algorithm is presented in literature [19]. To fully describe a technical system, a net of physical laws is needed in most cases; a chain would be sufficient for the simplest technical systems only. A single chain of physical laws usually contributes to realization of only one or a couple functions, compared to a larger number of functions which are needed to have a completely functional technical system.
The solution chain, presented graphically below, consists of a sequence of the friction law and the magnetic force law (Figure 8). Basic schemata are put together in accordance with the physical laws e.g. if two physical laws need gravity field for its realization the basic schemata should be put together

so that for both basic schemata gravity field has the same direction (see Figure 14). When combining the basic schemata into a solution schemata, wirk elements of one basic schemata can be superimposed on the same wirk element of the connecting basic schemata. The final shape of the solution is then achieved by shaping the wirk elements and supporting or connecting structure (Fig. 9).



$$\frac{F_g}{2} = F_{01} \longrightarrow F_{01} = F_{11}\mu \longrightarrow F_{11} = \frac{A_{21}B^2}{2\mu_0}$$

Figure 8. Solution chain with assembly of basic schemata.

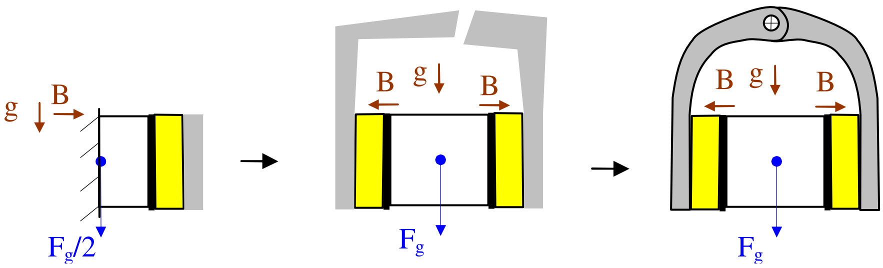
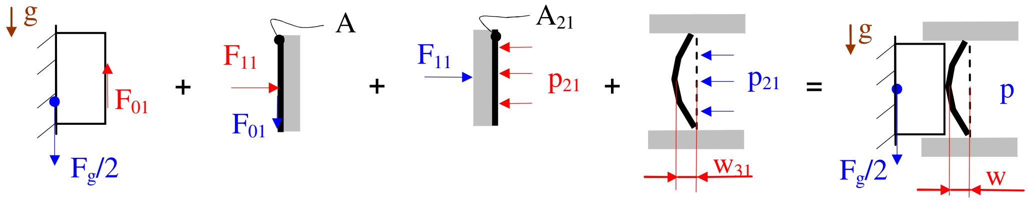


Figure 9. Shaping a solution out of wirk elements and supporting structure.

The schematic solution from Figure 10 consists of a sequence of the friction law, the static pressure law and the membrane flexion law. Surfaces from all three laws merge into the surface of the membrane. Final solution from Figure 11 uses a piston to generate the required static pressure.



$$\frac{F_g}{2} = F_{01} \longrightarrow F_{01} = F_{11}\mu \longrightarrow F_{11} = p_{21}A_{21} \longrightarrow p_{21} = 64D\frac{w_{31}}{\left(r_m^2 - r^2\right)^2}$$

Figure 10. Solution chain with assembly of basic schemata.

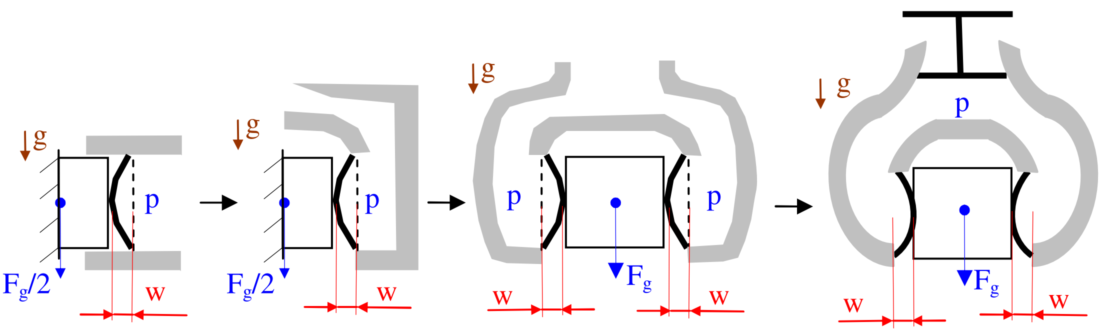
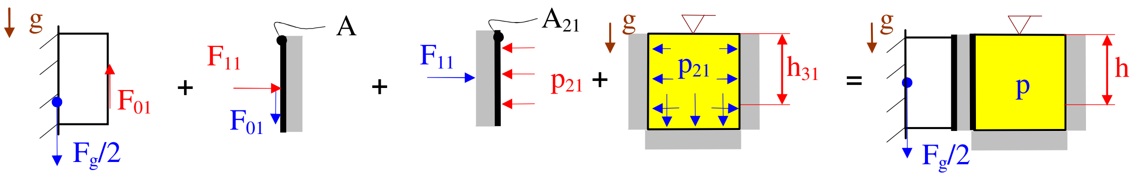


Figure 11. Shaping a solution out of wirk elements and supporting structure.

Figure 12 presents a schemata solution, similar to that presented in Figure 10. Instead of the membrane flexion law we applied hydrostatic pressure law as the third expression in the solution chain. The final solution from Figure 13 resembles the hydraulic press.



$$\frac{F_g}{2} = F_{01} \longrightarrow F_{01} = F_{11}\mu \longrightarrow F_{11} = p_{21}A_{21} \longrightarrow p_{21} = \rho g h_{31}$$

Figure 12. Solution chain with assembly of basic schemata.

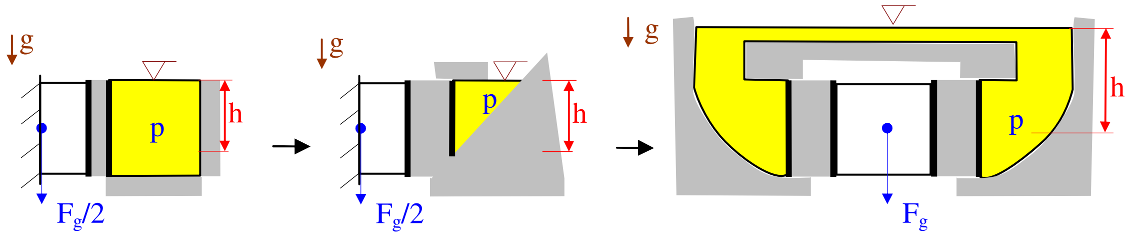
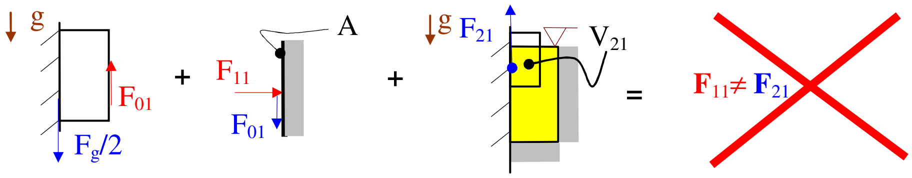


Figure 13. Shaping a solution out of wirk elements and supporting structure.

The chain of physical laws presented in Figure 14 does not provide a feasible solution without any additional connections between the friction law and the buoyancy force law. Direction of the buoyancy force (F_{21}) is prescribed by the gravity field and it is not congruent with a normal force from the friction law.



$$\frac{F_g}{2} = F_{01} \longrightarrow F_{01} = F_{11}\mu \longrightarrow F_{21} = \rho g V_{21}$$

Figure 14. Assembly of basic schemata does not give any solution for this chain of physical laws.

Some additional variants of the solutions from Figure 9, Figure 11 and Figure 13 could be generated by allocating wirk elements as shown in literature [2] and [17].

4 DISCUSSION

The described method is an attempt to use physical laws and chains of physical laws systematically with basic schemata which provide better understanding of technical systems and direct the engineers' attention to the vital parts for realization of a desired function. Such knowledge assists designers to optimize products, especially in the sense of structure sharing and function integration.

In most cases, single chains of physical laws are only a part of the technical system. Solution chains of physical laws tend to ramify when the number of physical laws in the chain increases. This happens even in the case of simple products such as a cloth peg described above.

Each part can potentially contribute to realization of several physical laws which have common wirk elements. Although more solution chains are feasible to fulfil a desired function, their level of fulfilment is not the same and must be evaluated through an analysis.

5 CONCLUSION

Graphical presentation of physical laws with basic schemata enables optimization of the technical systems through identification of wirk elements and their allocation. The method demonstrates the working principles which contribute to realization of a desired function.

Basic schemata are built from standard building blocks, which enable automated generation of graphical solutions. Because two successive physical laws share one variable (the output variable from

the previous law and the input variable from following law), it is possible to evaluate feasibility of such connection. For two successive physical laws, this is evaluated through their common variables, environment properties and position of wirk elements. The number of solutions largely depends on the number of physical laws from which chains are generated as well as on the chaining algorithm.
The final solution is not achieved simply by assembling the basic schemata. In the assembly process, wirk elements are merged and allocated but the final shape of a technical system needs to be designed by a designer.

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