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PHYSICAL NATURE OF TECHNICAL SYSTEMS

J. Rihtaršič, R. Žavbi and J. Duhovnik

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1. Introduction

The article presents a systematic approach to synthesis of a conceptual technical system (TS). The goal of the research is to formalize the structural embodiment of conceptual TS. The starting point for creating the structure of conceptual TS are physical laws, that are required to fulfil the desired function. In order to enable connections between individual physical laws and TS structure, basic schemata (BS) are introduced. Basic schemata consist of geometrical elements and physical quantities. They represent the necessary structure for realisation of the complementary physical laws. BS are applied for embodiment of the parts and they enable their assembly into complex TS. Connections between BS reveal physical nature of TS.

2. Background

Roughly speaking, two approaches to the synthesis of TS can be identified: a word synthesis, using a range of attributes, verbs and nouns, combined according to a defined set of rules, and a structural synthesis, using components that can also be presented descriptively but are usually presented symbolically.

Regardless of the approach used for generation of concepts, the final phase of their development requires a transition to their material embodiment. In our case, the synthesis means putting physical laws together with the aim to generate a structure of TS that will be able to fulfil the desired function. Doing “fast” and “right” in conceptual design phase shortens development time also in other phases of product development. Physical laws are important source of ideas for generation of new products as well as for upgrading the existing ones. A traditional product can become innovative again when the physical background is known and optimized. Generating conceptual TS on the basis of physical laws enables possibility of automation of concept generation process and knowledge about physical background of conceptual TS enables their better structural design.

The most direct transition from a physical law to a concrete TS is the use of analogue TS that already functions on the basis of a particular physical law. Together with the emergence of methods using function – physical law matrix, catalogues of existing TS have appeared. They function on the basis of selected physical laws [Koller and Kastrup 1994] [Roth 1994]. So generated schemata of conceptual TS are often overdefined and consequently the connectivity among such schemata is low. An alternative to overcome this problem is the use of individual standard components that make up a TS. Components bases provide knowledge and skills, integrated in the existing products, and are used to generate alternative TS designs. Chakrabarti, on the other hand, added working principles to the components that make up a structure of a TS [Chakrabarti 2004]. The synthesis of working principles starts with identifying the list of effects. They can be found in the effects database and have the same input variable as defined by the target function. The output variable is defined for each of these effects and is compared with the output variable of the target function. If the two variables match, there is a working principle that solves the target problem. Otherwise, the output variable of the effect is adopted as the input variable for the next iteration.

Souchkov treats the design process as a synthesis of primitive components which enable automated construction of more sophisticated products [Souchkov 1998]. Places at which a TS receives its inputs or delivers its effects are called action locations or wirk elements (WE) [Hubka and Eder 1988]. Point, line, surface and volume are action locations which also represent structural elements in the organ structural domain as well as in the constructional domain. However, the entire structure of TS does not contribute to its functionality [Ersoy 1975]. The structure at which TS does not receive inputs or delivers effect is called connecting structure.

The point, the line, the surface and the volume have been recognized as WE also in the case of the method where physical laws and their complementary BS are used for the purpose of the TS structural design [Rihtaršič et al. 2005]. Chains of BS are generated simultaneously with the chains of physical laws. Each physical law has complementary BS which represents the necessary structure for its realisation.

The method starts by selection of initial variable from the main function (Figure 1). Connections between functions and physicals laws that realize functions are usually not obvious. Most of the functions can be realised by several different physical laws and their combinations. For initial chaining variable (cause) the desired output variable is sought (effect). Connections between input and output variables are established via physical laws. Chaining algorithm works on the basis of causality. Causality describes relationship between causes and effects. Within the definition of causality, most technical systems are fully deterministic [Hubka and Eder 1988].

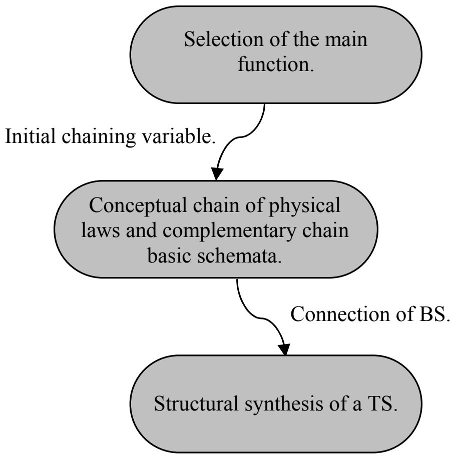

Figure 1. Procedure of structural synthesis with the use of physical laws and BS [Rihtaršič et al. 2005]

When functions are realised on the same WE, then these functions share structure of TS. Structure sharing means fulfilment of several functions or functional properties by the same physical structure [Chakrabarti, 2004]. Better designs tend to have more functions realised on the same structure.

From the structural point of view, it can be concluded that physical laws, on the basis of which a TS after all functions, have the biggest impact on not only the type but also the arrangement of WE. By connecting appropriate WE from different physical laws, we are supporting structure sharing.

3. Connecting structures of a TS

In their Theory of Technical Systems Hubka and Eder present TS on several levels: functional structure, organ structure and component structure, transformation process and technology [Hubka and Eder 1988]. In our approach to building a concept TS, the verbal description of a function has been replaced by chains of physical laws. Physical laws enable a function to be realized. Functional structure is followed by the organ structure and the component structure. This orientation has been followed also within our approach to synthesis of conceptual TS. The organ structure is made up of WE, which are also forming element of BS. Basic schemata require material properties of WE, as well as the necessary type, number and spatial arrangement. Together with the chain of physical laws, the BS chain provides elementary design of TS. On the level of TS component synthesis, BS are combined and shaped. During the TS assembly process, evoked functions between individual components may come up.

3.1 Connecting BS

The BS consists of geometric elements and physical properties (Figure 2). Each BS consist of at least one WE and at least two connecting physical quantities, representing the cause and effect. Besides the connecting physical quantities, a BS can also have conditional properties (environment, boundary, material and geometric properties). Chaining of physical laws is performed via causes and effects [Žavbi and Duhovnik 2001]. BS further enables chaining also via WE and conditional properties. Depending on a physical law, BS often consist of more than one WE which may be identical or different.

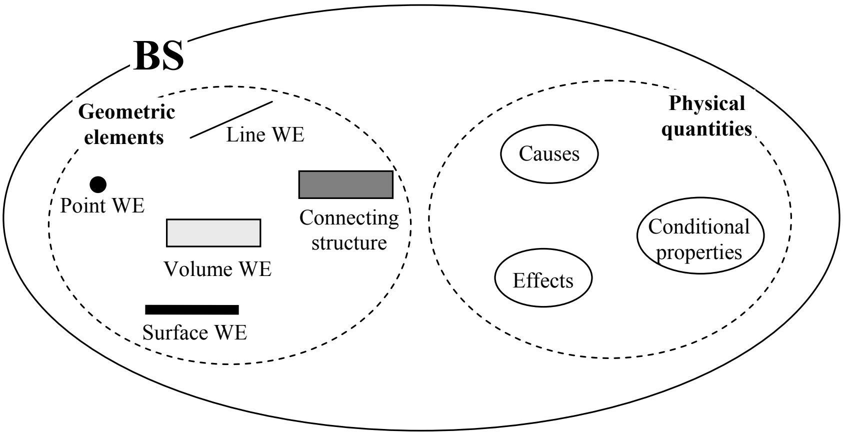

Figure 2. Constituent elements of a BS

3.1.1 Connections between WE

In the case of connections between two BS via point WE, the point WE can connect with all other types of WE and with the connecting structure (Figure 3a), while the line WE can connect with another line WE, surface WE and volume WE and with the connecting structure (Figure 3b). The surface WE can further connect with another surface WE, volume WE and the connecting structure (Figure 3c). In such a case, properties of the surface WE are completely transferred onto the connecting WE. Volume WE can connect with another volume WE and with the connecting structure (Figure 3d). In such a case, the joint volume WE has all properties of both individual volume WE. Connecting structure can connect with volume WE and with another connecting structure (Figure 3e). The connecting structure has no pre-determined properties. When the WE connects with the connecting structure, the latter acquires its properties. If properties of two WE are not compatible (e.g. one volume WE is conductible and the other volume WE is insulator), than such two WE can not be connected into one WE.

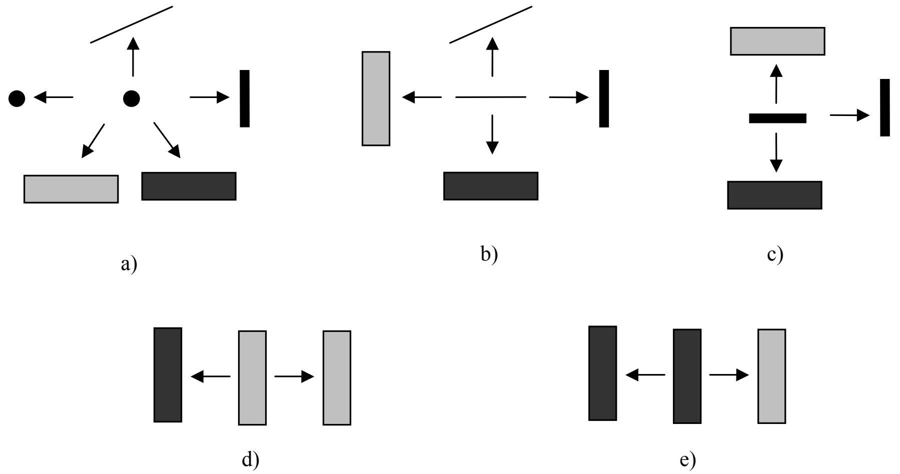

Figure 3. Possible connections between WE: a) connections with a point WE, b) connections with a line WE, c) connections with a surface WE, d) connections with a volume WE and e) connections with a connecting structure

Example where three BS are connected with a surface WE is shown in Figure 4b. Figure 4a shows a tapered shank for securing cutting tools and other accessories to a rotating spindle. Tools are slipped into the spindle and the axial force (F_{01}=F_{11}) drives the tapered shank tightly into the tapered hole. Due to the tapered surface the normal force (F_{31}) appears which causes surface pressure (p_{21}) and friction force (F_{32}) that provides a torque transmission (M_{41}). Surface WE from three BS that represent wedge law (A_{11}), surface pressure law (A_{21}) and static friction law (A_{31}) are combined into a single surface WE (A_{i1}) (see also Figure 5). Geometry of the tapered shank is further defined also by the taper angle (β_{11}) and by the diameter of the shank (L_{41}).

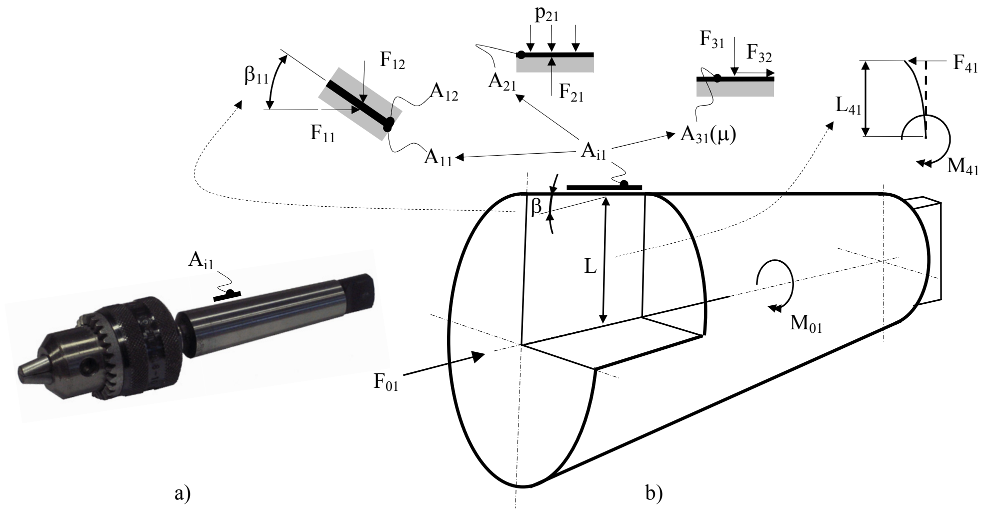

Figure 4. Connecting three BS into common surface WE (A_{i1}), (β - taper angle, F-force, A – surface, p – surface pressure, M – torque, L – length)

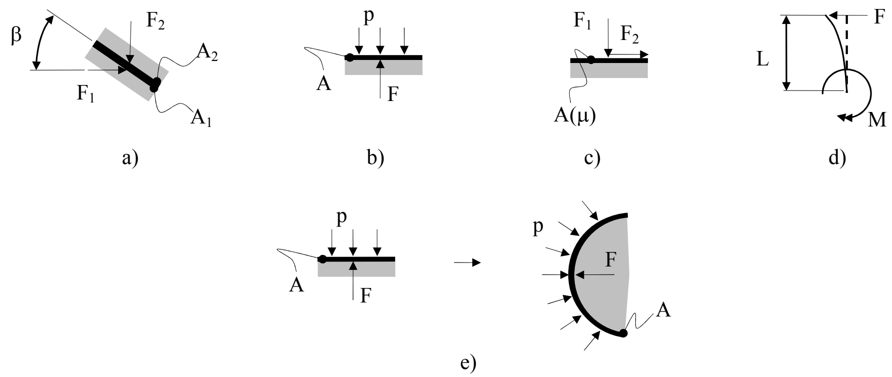

Figure 5. BS that represent following physical laws: a) the wedge law, b) the surface pressure law, c) the static friction law and d) the torsion law, e) change of BS shape

When WE elements are synthesized into a part, the shape of the WE may be optionally shaped as long as the effect of the physical law can be realised. The straight surface in a BS that represents pressure surface physical law is reshaped into circular surface to present a surface of the tapered shank (Figure 5e). Variants of a TS can be further generated by allocation of WE. Identical function can be realized by different structures, their properties are defined by constituent elements and their relations [Hubka 1973]. Flexibility of WE enables variety of forms of the same TS, however, their functionality is usually not the equal. More examples of component structural synthesis of TS with use of physical laws and BS are presented in [Rihtaršič et al. 2007].

3.1.2 Connections between physical quantities

Chaining of physical laws is performed via causes and effects. In case there is a reversible connection between two connecting physical quantities, the status of a physical quantity (cause or effect) can change. On the other hand BS can further connect to another BS via causes and effects as well as via conditional properties. Two BS are connected via causal physical quantity when they form a common cause (both have the same causal physical quantity) that is entering a third BS. Two BS are connected via an effective physical quantity when they form a common effect (both have the same effective physical quantity). Conditional properties enable connections via physical quantities that are part of a physical law; however, they can not be used for chain generation (namely, only a cause or an effect can function as a chaining physical quantity). Two physical laws inside the same chain of physical laws or between two chains of physical laws may use the same conditional physical variable which connects them into a system of chains.

3.1.3 Examples of connections between BS

The main TS function is usually fulfilled after a relatively short chain of physical laws. The number of physical laws in a chain, forming the "backbone" of the TS, is usually low also for more sophisticated TS. In this case, the sophisticated TS include not only multifunctional systems but also monofunctional ones, where energy conversions occur. The number of evoked physical laws is often much higher than the number of those involved in the main chain (i.e. the backbone) of physical laws. The accompanying physical laws mostly evoke with more detailed TS, where concrete TS components are already used. Additional physical laws or chains of physical laws are used to fulfil also partial functions. Connections among chains of physical laws and among chains of BS must be possible to be able to fully describe a TS.

Figure 6a shows a symbolic presentation of a most simple BS construction. It is represented by a big bold circle and it enables connections via a cause, an effect and WE. The cause and effect are represented by two small bold circles while WE is represented by a filled circle. Small thin circle represents conditional property of BS. Symbolic presentation from Figure 6b presents a BS composed of a cause, an effect, two conditional properties and two WE.

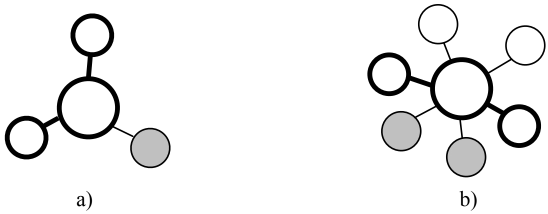

Figure 6. a) Most elementary BS composed of a cause and an effect variable and one WE; b) BS composed of a cause and an effect variable, two conditional properties and two WE

As described in [Žavbi and Duhovnik 2001], automated chaining generates connections between physical laws only via causes and effects as shown symbolically in Figure 7a. BS chain is based on chain of physical laws and it is also connected via causes and effects. However connections among chains of BS or among individual BS can be established also via conditional properties (Figure 7b) and via WE (Figure 7c). Several simultaneous connections between two BS are possible. Figure 7d shows an example where two BS are connected simultaneously via the connecting variable and conditional property. More than two BS can also be connected simultaneously (Figure 7e) (see also figure 4b).

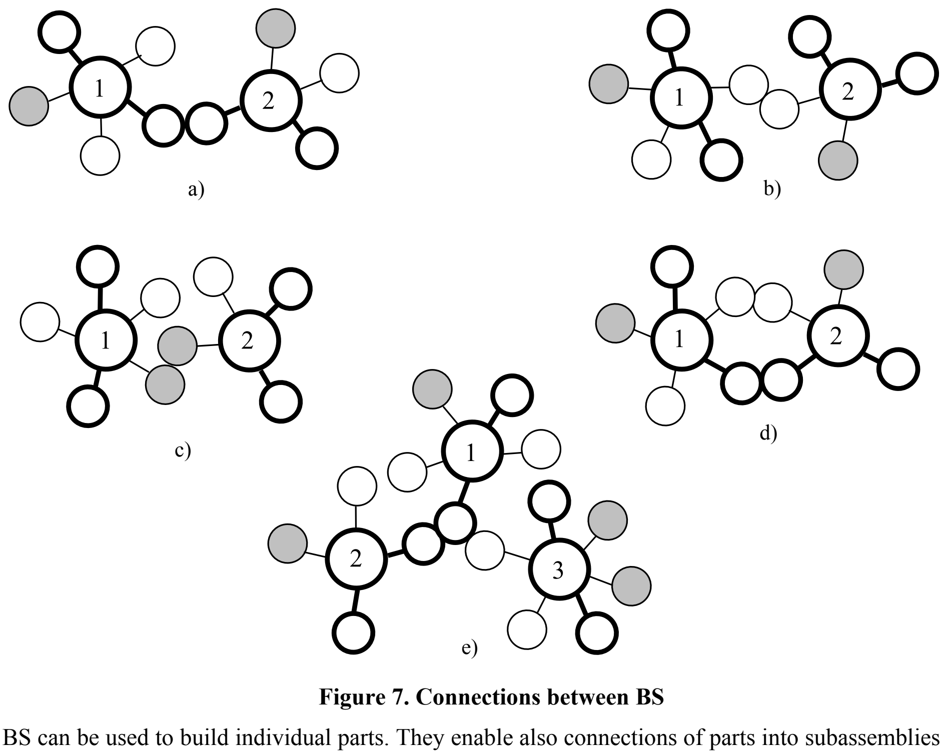

Figure 7. Connections between BS

BS can be used to build individual parts. They enable also connections of parts into subassemblies and further into complex TS. Figure 8 shows symbolic TS, composed of six BS. The backbone of the system is represented by three BS (1, 2, 3), connected via causes and effects. The shorter chain of two BS (4, 5) connects onto this chain via the conditional properties. Here, the connection between BS 4 and BS 5 is not performed only via the connecting physical quantity but also via the conditional physical quantity. Another BS (6) is connected with the main chain via WE.

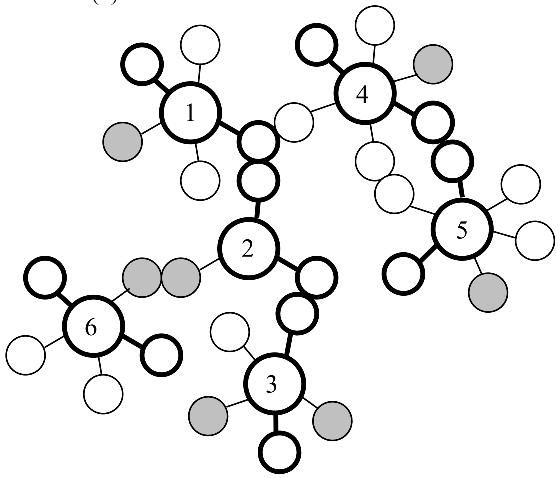

Figure 8. Types of connections within TS

Connections analysis of existing TS provides an insight into a better understanding of TS. Indirectly, it also reveals its deficiencies. As mentioned above, all connections have a physical background; in the case of specific TS, we can focus on individual types of connections, which can be of mechanical, electric, thermal, acoustic or other natures. In this case, we should make use of the fact that physical laws are brought to effect on WE. By knowing the connections among WE, we can analyse transmission of heat, propagation of noise, etc.

4. Discussion

Research of complex technical systems (TS) brings us to the conclusion that besides the chains of physical laws that describe their main functions, there are also many auxiliary chains of physical laws that fulfil their partial functions. Some chains of physical laws are established as early as in conceptual design phase where conceptual TS are generated, some are evoked during the process of assembling individual components and sub-assemblies (e.g. mechanical connections) while some appear during the operation of a TS. For the purpose of structural synthesis of conceptual TS, physical laws are further described with their complementary BS. A physical law represents a connection between the causal and effective variable. Possible remaining physical variables within a physical law have been termed conditional properties. If the same conditional physical variable appears in one of the remaining physical laws, the mutual connection is also possible via this conditional physical variable. The conditional physical variable refers to boundary conditions (e.g. loading, fixation,...), environment, material and geometric properties. Besides physical quantities, BS connects with another BS via the geometry, represented by WE as shown in Figure 4b. Individual part is mechanically connected into TS assembly with at least one WE, but most often is connected with several WE.

Based on the inclusion of individual components' WE into fulfilling the main, partial and auxiliary functions, we can evaluate the appropriateness of the component structure and utilization of component material. From this point of view, we can then try to modify or even remove parts of the components that are not aimed at fulfilling any of the functions or can even have a negative effect on functionality of the TS.

Description of TS with physical laws and with complementary BS provides knowledge about how TS works. This information is stored and may be retrieved at lather time when modifications or upgrades of such TS are made.

5. Conclusion

TS are man's artificial product and they function exclusively on the basis of physical laws. The article has defined possible types and ways of connections between individual physical laws within the same TS. For the purpose of a structural synthesis of TS, basic schemata were introduced. They are complementary to physical laws and consist of a finite number of physical variables, constants and WE. Properties and BS structure has been described in [Rihtaršič et al. 2005]. Definition of mutual connections establishes rules that enable synthesis of computer tool. BS support synthesis of the individual parts as well as their integration into complex TS. The method can be used in different domains of physics, but the designer is required to possess a basic knowledge of the applied physical laws. Nevertheless, it also allows explanation of TS functioning and this fact results in the possibility to improve its structural design.

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Janez Rihtaršič
Researcher
University of Ljubljana, Faculty of Mechanical Engineering, LECAD laboratory
Aškerčeva 6, 1000 Ljubljana, Slovenia
Tel.: + 386 1 4771 775
Fax.: + 386 1 4771 156
Email: janez.rihtarsic@lecad.uni-lj.si
URL: http://www.lecad.uni-lj.si/