2 PROPERTIES OF ELEMENTARY STRUCTURAL ELEMENTS FOR SYNTHESIS OF CONCEPTUAL TECHNICAL SYSTEMS

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Structural synthesis of conceptual technical systems is a result of transformation from the functional domain into the structural domain. To enable semi-automated synthesis of conceptual technical systems on the basis of physical laws basic schemata have been introduced. Basic schemata are complementary to physical laws and consist of four elementary structural elements (point, line, surface and volume).

In the presented paper, we discuss the properties of structural elements for synthesis of conceptual technical systems and how they are used to support variant design. Engineers from different engineering domains were asked to generate conceptual technical systems on the basis of automatically generated chains of physical laws and on the basis of the complementary chains of basic schemata. It was shown that engineers with different educational background and experiences will generate different conceptual structures, although concepts operate on the basis of the same physical laws.

Keywords: Conceptual Design, Computational Synthesis, Basic Schema, Physical Law.

1. ELEMENTS AND METHODS USED FOR GENERATION OF CONCEPTUAL TS

In the conceptual design phase, technical systems (TS) are developed up to a stage where they indicate a possible solution for a required function; however, details still need to be evolved. The most straightforward (intuitive) way to generate a structural conceptual solution for a given technical problem is by drawing sketches based on a designer's experience and knowledge. Idea generation and structural evolution can be further supported by the use of a function-physical law matrix,[1] by the use of catalogues of parts or by the use of catalogues of simplified TS.[2] Koller[3] and Ehrlenspiel[4] identified the following structural elements for embodiment of TS: points, lines, surfaces, parts, part assemblies, machines, appliances, apparatus, aggregates and complex technical systems.

The first three (points, lines and surfaces) are, together with the volume element, often used as basic generic elements in different models for structural synthesis. These generic elements are called action locations or wirk elements (WE). In the theory of technical systems they are used to constitute organs.[5] An organ represents the required structure for a complete realisation of a desired function. A total function is realised by an organ structure. Examples of structural synthesis using organs are shown in practical studies in systematic design.[6] For an efficient integration of method results, the use of computer-assisted methods is essential.[7] The computer-aided catalogues offer substantial advantages compared to textbooks e.g. easy modifications, integrated calculations, clarity and fast performance. To computationally build an initial organ structure, Malmqvist[8] used bond graphs. Relationships between bond graph parameters and physical attributes of the organ are stated by characteristic equations that maintain a link between physical attributes and functionality.

An alternative approach towards structural synthesis was presented by Chakrabarti.[9] For development of solution principles and conceptual structures, Chakrabarti introduced the following constructs: variables, properties, constraints, effects and components. A conceptual structure is made by synthesis of components. A component represents an object that has a set of properties that can help activate effects. The component database is searched to find all possible component alternatives that can satisfy properties and constraints required by the solution principle.

In our investigations, we adopted some features of the above-mentioned methods and expanded them in the direction of graphical representation of conceptual TS. Thus, the starting point of the following research is how to represent physical laws and structures to enable connections on the level of a system of physical laws that realise a desired function.

Such a computerised model, operating on the basis of physical laws from different domains of physics, demands a high level of formalism to enable generation of a structural synthesis of TS. Every physical law is graphically represented by complementary basic schema. The chain of physical laws and chain of basic schemata enable formulation of a conceptual technical system simultaneously on the abstract, as well as on the concrete, structural level. The initial structure of the conceptual TS can be further developed into more detailed conceptual solutions by redesigning the WE.

2. PROPERTIES OF BASIC STRUCTURAL ELEMENTS

Generation of a conceptual TS starts with the search for desired effects among physical laws. The advantage of this approach is that we are able to generate from a relatively small set of physical laws a large number of working principles. Use of physical laws also provides more flexibility when searching for solutions from different technical domains. Working with physical laws further provides the fundamental knowledge about structural (shape, topology, materials,…) impacts on the functionality of the conceptual technical system.

These features demand the following properties from the basic generic structural elements that are used to present physical laws:

- basic structural elements must enable structural representation of physical laws from different domains of physics,
- basic structural elements need to enable flexible shape design,
- basic structural elements need to enable connectivity among physical laws to also provide solutions in cases where several physical laws are needed for realisation of a desired function.

The first step towards structural generation of conceptual TS with the use of physical laws is structural representation of physical laws. This is done by composition of basic structural elements (WE) and physical quantities needed for realisation of physical laws. Compositions that represent physical laws in this way are called basic schema (BS).

The BS consists of geometric elements and physical properties.[10] Each BS consists of at least one WE and at least two connecting physical quantities, representing cause and effect. Besides the connecting physical quantities, a BS can also have conditional properties (environment, boundary, material and geometric properties). Constituent elements of a BS are shown in Figure 1. Point WE, line WE, surface WE, volume WE and connecting structure are used to generate a structure of a BS and are also used for structural connections among several BS.

2.1. Design Properties of WE

To be able to present the geometry of the conceptual structure of a TS, WE need to have flexible design properties as well as good connecting properties. Choice of colours, type of lines, length and width of WE increase the clarity of the structural presentation. Symbolic or textual description provides additional explanation of the conceptual TS.

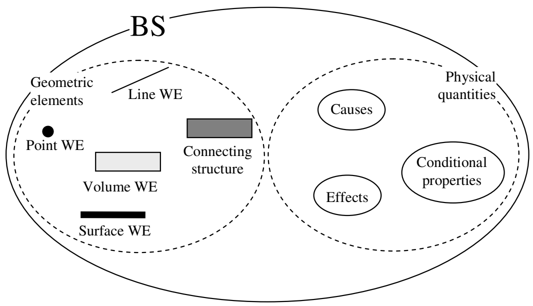

Figure 1. Constituent elements of a BS.[10]

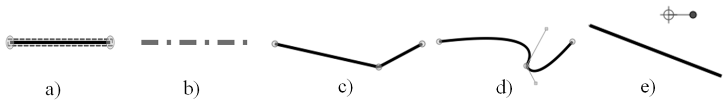

Figure 2. Design properties of a line WE.

2.1.1. Design properties of a point WE

Points are essential part of lines, surfaces and volumes although they alone are rarely used for representation of conceptual structure. Points are, however, often used for applications in reverse engineering and pattern recognition. In the structure of technical systems, points can be identified as corners, nibs, contact spots between surfaces, centres of gravity, etc. For this reason, point WE have the same properties as the WE to which they belong. Two or more points define the shape of the TS (Figure 2c). Points can be further added or removed from all other structural elements and are sometimes used as control points for curve generation (Figure 2d).

2.1.2. Design properties of a line WE

The initial or neutral form of a line WE is set as a straight solid line which is defined by the start and end points (Figure 2a). The length, width, type of line and its colour can be changed (Figure 2b). By adding points we can produce an arbitrary line shape which can still be straight and cornered (Figure 2c) or can be a smooth curve (Figure 2d). The shape of the curvature is defined by one or two control points. Control points define inclination of the curve in the active point of the curve. The distance between the active point and the control point defines the dimensions of the curve between two neighbouring points. Further geometrical manipulations are enabled with the rotation of the curve, where the rotational pole can be selected arbitrarily (Figure 2e). When the line is needed only for clarification reasons, the status of the line is changed to dummy (Figure 3).

2.1.3. Design properties of a surface WE

Due to two-dimensional representation of an automatically generated conceptual TS, the surface WE is initially represented as a thick solid line. Thus, the properties of surface WE are identical to those of line WE.

2.1.4. Design properties of a volume WE

A volume WE is by default represented as a filled square with black edges (Figure 4a). Dimensions of the volume WE are changed by activation and moving of the control points (Figure 4b). The shape of the volume WE edges is changed by points which can be added or removed from volume WE edges (Figure 4c and Figure 4d). Figure 4e shows rotation of a volume WE with the centre of rotation inside

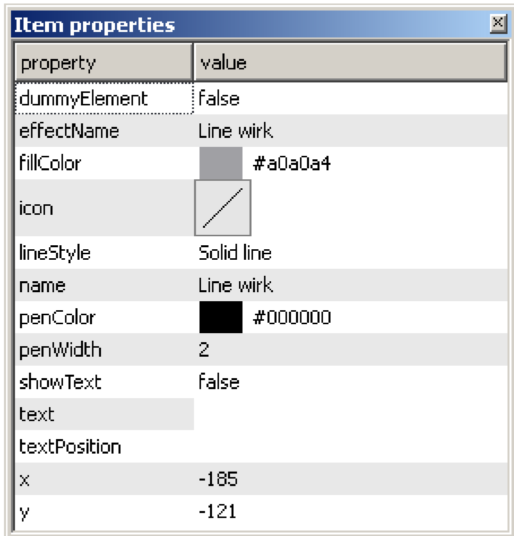

Figure 3. Menu with design properties of a line WE.

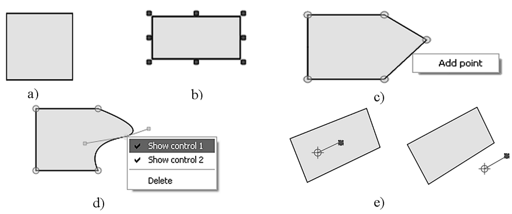

Figure 4. Design properties of a volume WE.

the WE and rotation with the centre of rotation outside of WE. Volume status can be changed to dummy if it is needed for clarification reasons (Figure 5).

2.1.5. Design properties of the connecting structure

A connecting structure is used to connect several WE into a part. With integration of WE into the connecting structure, the properties of WE become the properties of the connecting structure. As with a volume WE, a connecting structure is initially represented as a filled square with black edges.

2.2. Connecting Properties of WE

Structural synthesis of a chain of physical laws that are needed for realisation of a desired function is performed by connecting active WE into the structure of the conceptual TS. WE are identified from the chain of BS. WE are connected or separated with each other over points, lines and surfaces.

By activating points, we can connect a line WE with another line WE (Figure 6a), with another surface WE (Figure 6b), with another volume WE (Figure 6c) and with the connecting structure.

Surfaces as well as volumes can be mutually connected over the points (Figure 7a to Figure 7c) or over the surfaces (Figure 8a to Figure 8c). When the connection is established over the surfaces, then the surface that is being connected takes over the shape of the surface that it is being connected to (Figure 8c).

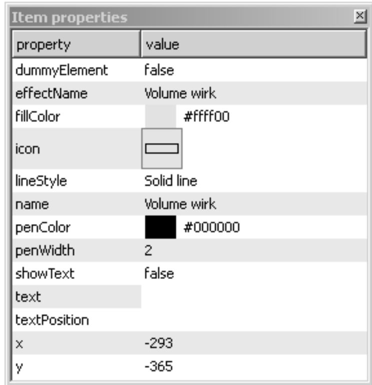

Figure 5. Menu with design properties of a volume WE.

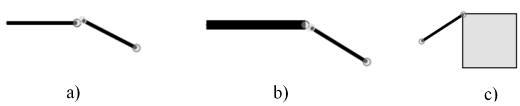

Figure 6. Connection of a line WE with another a) line WE, b) surface WE and c) volume WE.

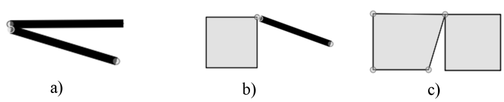

Figure 7. Connection among surfaces and volumes over the points.

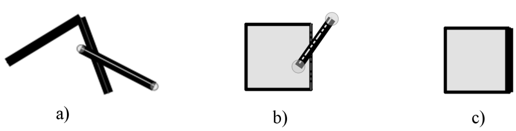

Figure 8. Connection among surface and volume WE over the surfaces.

3. EMBODIMENT OF A CONCEPTUAL TS

An important mechanism in structural optimisation of conceptual technical systems is structure sharing. Structure sharing means fulfilment of several functions or functional properties by the same physical structure.[9] Similarly, effects of physical laws can share the same structure. In the following text we will present an example of structural synthesis of a conceptual TS that generates pressure. The example was performed in a computer program called Sophy (Synthesis of physical laws) which was developed at Faculty of Mechanical Engineering, University of Ljubljana. The program provides support in idea generation and synthesis of conceptual TS.

Generation of conceptual TS starts with selection of the physical laws and chaining variables which enable realisation of the required function.[11] Further the variables which start (causes) and end (effects) chaining process are specified. Physical laws represent the connections between causes and effects. The first physical laws in the chain are those that contain selected causal variables. If the output of these physical laws are desired effects than chaining algorithm stops. Otherwise the output variables from the first physical law represent the input variable for the next physical law in the chain. Chains

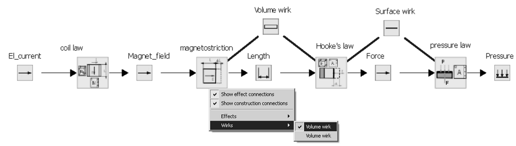

Figure 9. Map of connections over physical variables and structural elements within a single chain.

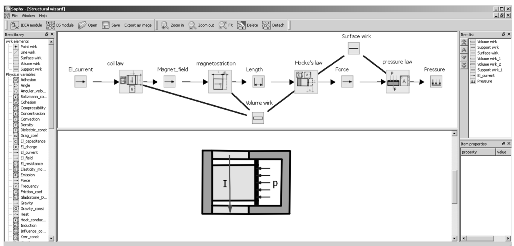

Figure 10. Synthesis of a conceptual TS.

that contain specified input and output variable represent the possible solution for realisation of the desired function. Together with chain of physical laws the chain of complementary BS is generated (Figure 9).

Structural synthesis is performed in two steps:

- the chain or several chains of BS are selected from the list of results which were automatically generated on the basis of the chaining algorithm and
- the WE from the BS are formed into conceptual TS.

Physical laws are connected over the cause and effect variables while basic schemata can be additionally connected over WE. By activating the BS icon, it is possible to visualise the physical variables and WE which compose BS and which are further used to develop a map of connections between physical laws and structure of the conceptual TS (Figure 9). If two effects from different physical laws are realised on the same WE, then the common WE connects these two physical laws. E.g. the magnetostriction law and Hooke's law share a common volume WE, while Hooke's law and the pressure law share a common surface WE.

Icons present the BS of individual physical laws. By dragging the BS icon into the design space window, the constituent geometric elements and physical quantities of the BS appear (Figure 10). Additional physical quantities and geometric elements can be imported into the design space window from the library of all geometric elements and physical quantities. Additional quantities and elements are sometimes needed to enable diverse conceptual solutions, as shown in Figure 11. The BS provides information about spatial arrangement of geometric elements and about physical quantities that influence the functionality of the conceptual TS.

In design space, WE are combined or detached, added or deleted and formed as shown in section 2 of this paper. This part of the synthesis process is done manually by the design engineer. On the basis of the BS chain from Figure 9, the conceptual TS in Figure 10 was embodied.

To find out whether it is possible to generate different structural solutions for TS that operate on the basis of an identical chain of physical laws, we asked experienced design engineers with different educational background (physics, mechanical engineering and electrical engineering) to develop their conceptual solution for the chain from Figure 9.

As the result of the synthesis process, three different embodiments of the conceptual TS were formed (Figure 11). They differ in completeness, functionality and applicability aspects. This emphasises

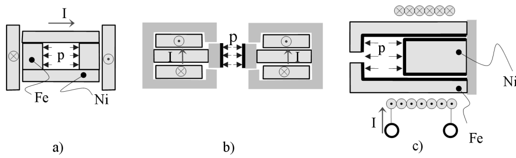

Figure 11. Diverse conceptual technical systems designed by three different authors, based on the same chain of physical laws and basic schemata.

the need for freedom in embodiment provided by geometrical elements. In Figure 11c, the coil was symbolically presented by small circles with dots and crosses instead of the two rectangles indicated by the BS. In Figure 11a and in Figure 11c, the two design engineers made a textual remark to label the material type, which influences the functionality of the conceptual solution.

4. CONCLUSION

Chaining of physical laws enables inventive conceptual solutions which may not be found in the catalogues of working principles. By chaining algorithms and input data, it is possible to control the number of generated solutions; however, the final evaluation and selection is up to the design engineer. A chain of basic schemata visually supplements a chain of physical laws in structural embodiment of a so-generated TS. Physical laws and BS provide information about the physical quantities and geometric features that influence the performance of the conceptual TS.

In spite of the fact that the same chain of physical laws was used in all three cases from Figure 11, the generated conceptual TS are applicable for diverse purposes (clamps, pumps, etc.). The purpose of the solutions was strongly connected with each design engineer's professional experiences. No conceptual TS was fully developed, which indicates the need for designers to be allowed to have some vagueness in structural synthesis of conceptual TS. Although the solution was triggered and influenced by the generated chain of BS, the designers introduced symbols that they are familiar with (i.e. the coil symbol) and sometimes text was added for explanation. Additional description of some effects (i.e. influence of magnetic field on elongation or contraction of different metals) of physical laws was found helpful when designing a conceptual solution to fully employ the effect of physical laws.

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