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GRAPH REPRESENTATION OF PHYSICAL EFFECTS NETWORKS IN CONCEPTUAL DESIGN

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ABSTRACT

This paper proposes a graph representation of networks of physical effects for supporting the generation of alternative solutions in conceptual design. Physical parameters are herein understood as elements which have physical effects as input and output. Physical parameters can be linked to other physical parameters by physical effects that match their respective input and output. For a given design problem, if both a starting parameter and a desired end parameter are known, lists of physical effects can thus be used to build a network of physical effects that encompasses all physically possible solutions. This network can be displayed using graph representations, constituting a solution space on the physical effect level of abstraction. Via the application of constraints, valid chains of physical effects to a given design problem can be extracted. Examples of use are given and transforming the graph representation to design structure matrix methodology is discussed.

Keywords: Physical effects, graph representation, conceptual design, solution space, DSM.

1 INTRODUCTION

In conceptual design, alternative solutions to design problems are sought after in early stages. To that end, design problems can be abstracted to physical effects (e.g., “transform electric energy into torque”). When a design problem is described on this level of abstraction, lists of physical effects can greatly widen the solution space [1], [2]. Typically, these lists are assorted according to input and output parameters (e.g., electric current and mechanic torque). Examples for lists of physical effects can be found in [2], [3] and [4].

For a given design problem that has input and output parameters defined, a list of physical effects can provide potential solutions to solve the problem (if there are effects which output parameters match that of the design problem). In case there is no effect that has the starting parameter as input and the end parameter as output, chains of physical effects can be built that – through multiple physical effects – generate the desired output.

When complex systems ought to be visualized, graph representations constitute an appropriate option [5], [6]. In graphs, elements (for the problem at hand, physical parameters) can easily and intuitively be connected by dependencies (physical effects). The resulting networks can be understood intuitively, and offer a useful representation of complex systems for discussion in teams. They can easily be modified and navigated, and can help to enhance teamwork. In addition, graphs can automatically be transformed into matrices and vice versa, which opens broad possibilities for further computation.

In combining lists of physical effects and representation via graphs, this paper proposes an extension to idea generation in conceptual design. With graph representation, networks of physical parameters can be visualized and benefit idea generation. The paper shows how to build and constrain a network of physical parameters, gives examples, proposes further enhancement of the graphs via attributes of dependencies. This approach is similar to bond graphs as discussed for example in [7], [8]. The network proposed herein focuses on depicting one network of physical effects to a single design problem. However it encompasses all physically possible solutions, rather than analyzing a given system architecture. The paper references applications, and discusses the transformation into Design Structure Matrix (DSM) methodology.

2 BUILDING RULES IN PHYSICAL EFFECTS NETWORKS

A physical effect can be understood as two elements (physical parameters, e.g. torque and force) linked by a dependency (physical effect, e.g. lever). Physical effects can link more than two different physical parameters. For graph representation, they can be applied to all pairs of elements. A simple example in Figure 1 shows the graph representation of the physical effect "lever" to all pertaining parameters torque τ, force F and momentum arm r.

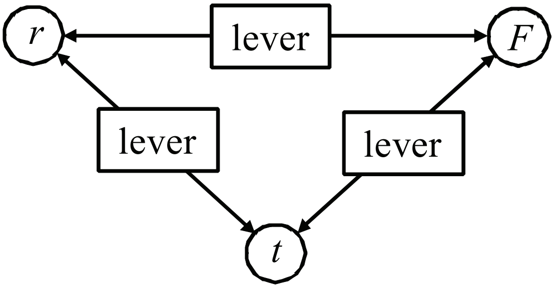


Figure 1. Graph representation of a physical effect

This form of representation in itself seems much less comprehensible than expressing the effect in a simple equation $\tau = F \ x \ r$. However, the parameters now are decomposed visually and allow for interconnecting with other effects that have the same parameters as in- and output. Building on the above example, the physical effect "compressive force" and its pertaining parameter pressure p are introduced and connected to the force parameter. This is shown in Figure 2, omitting the momentum arm r from the previous figure 1.

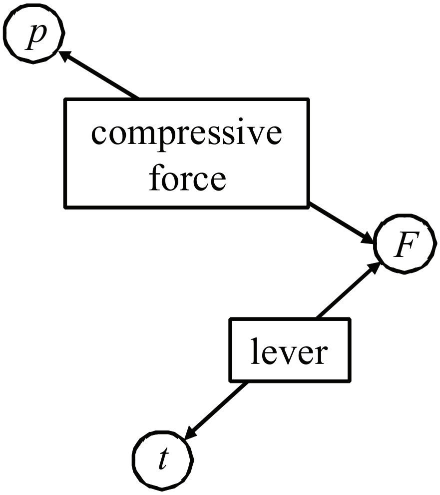


Figure 2. Graph representation of a chain of physical effects

For many pairs of physical parameters, more than one physical effect exists that can interconnect them. For instance, both "lever" and "Hooke's law" transform force into a distance (momentum arm r for lever effect, and deformation x in Hooke's law). Generalizing from the momentum arm r and the deformation x to any spatial distance d, both effects can be applied to the same pair of parameters. The resulting graph is shown in Figure 3.

Figure 3. Graph representation of multiple physical effects to a pair of parameters

The building rules thus are a) to **decompose** physical parameters and physical effects (as shown in figure 1), then to b) **interconnect** different effects that have the same physical parameter (as shown in figure 2), and ultimately to **integrate** multiple effects which apply to the same pair of parameters (as shown in figure 3). Using these simple rules, a network of physical effects can be formed. For a given physical parameter, all pertaining physical effects can be linked to all related parameters. Successively, all effects of a given list of physical effects can thus be used to build a large graph that represents the physical space of that list of effects.

Assuming a few dozen effects and even more parameters, the resulting graph would rather be unwieldy, though. In order to put the graph representation into use more efficient use in idea creation, both a building procedure and constraints for a given problem are needed, so as to constrain growth and early on rule out unsuccessful or inefficient designs.

3 BUILDING PROCEDURE AND CONTRAINTS

The graph representation of physical effects networks shall support idea creation in the conceptual design phase of a specific design problem. A specific design problem is understood herein as not more than both a starting and a termination point in the form of a physical parameter. The result encompasses a multitude of possible chains of physical effects that can transform the start parameter to the end parameter. They can thus later be used in concept design to create ideas for different architectures.

3.1 Preparation

The first step in building a physical effects network is to identify the start and end parameters of the design problem. When using physical effects for idea creation, these should normally be known or can easily be derived from a functional model or a list of requirements.

In this paper, the idea creation for alternative solutions to a pressure converter serves as an example. The pressure converter is employed in railway brakes, and converts a variable air pressure p of the control pipe into a corresponding air pressure p' in the brake valve. The start and end parameter of the given example thus both are pressures, p and p'.

As a second step of preparation, constraints must be defined that limit the growth of the physical effects network. Constraints are herein understood as criteria for exclusion of physical effects. Without applicable constraints, the physical effects network would encompass all available physical effects, and the huge, resulting graph would not support idea creation for its lack of intuitive understanding. Physical effects offer a magnitude of characteristics that can serve as constraints for a given design problem. An exemplary list of constraints is given in Table 1, other constraints may apply to other design problems.

Table 1. Constraints for physical effects networks

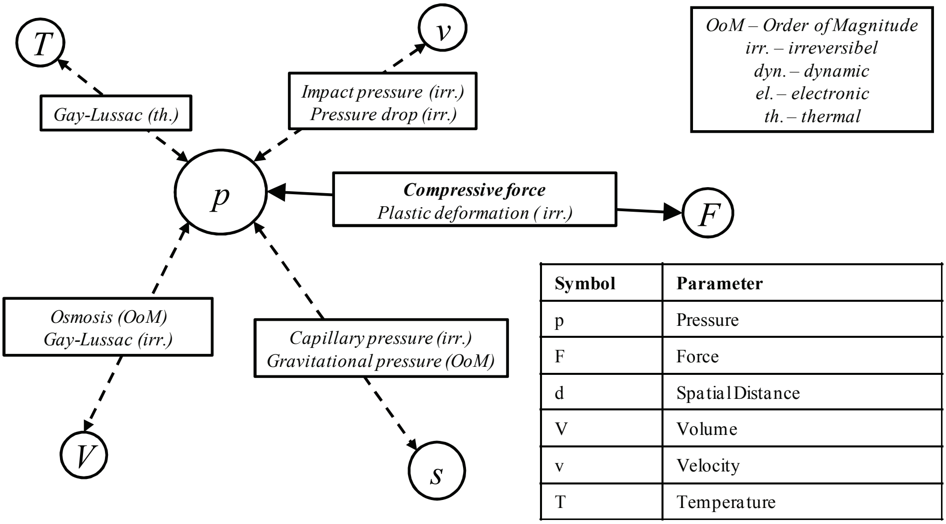
Constraint	**Example of Invalid Physical Effect**
order of magnitude	capillary pressure
irreversibility	osmosis
dynamic	coriolis force
electric	Ohm’s law
independent of orientation	gravitational force
efficiency	sound pressure

Which constraints apply to a given design problem can be determined from lists of requirements and / or functional modeling. Following the example of the pressure converter, a valid solution to the problem must be reversible, able to serve statically without loss of energy, independent of orientation and temperature, able to provide the necessary output pressure *p'* within an order of magnitude of the input pressure, and must not rely on electric nor chemical effects.

3.2 Building the Network

When start and end parameters as well as constraints have been established, the physical effects network can be built up starting from either the start parameter or the end parameter of the design problem. Building the physical effects network is done by subsequently following through a two-step iteration: First, for the chosen parameter, all applicable physical effects are subsequently linked to the start parameter and the respective output parameter. Second, all physical effects that do not fulfill one or more constraints are marked by a dashed line, as well as their respective output parameters. For the pressure converter example, the first application of the building routine provides the graph shown in Figure 4.

The iteration of adding physical effects and subsequently checking for constraints is repeated until all applicable effects have been assigned to all valid parameters. The physical effects network is then complete and constitutes a solution space on the physical level of abstraction for the design problem. For the pressure converter example, the complete network is shown in Figure 5. Note that some physical parameters appear twice. This is done to prevent the dependencies from overlapping and in the case of force *F* and force *F'*, to show the physical effects that interconnect both. The example has a rather confined solution space, which stems from the steep constraints. It becomes visually apparent that without altering the constraints, not many alternative solutions can be derived.



Symbol	**Parameter**
p	Pressure
F	Force
d	Spatial Distance
V	Volume
v	Velocity
T	Temperature

Figure 4. Graph representation of physical effects network after first iteration

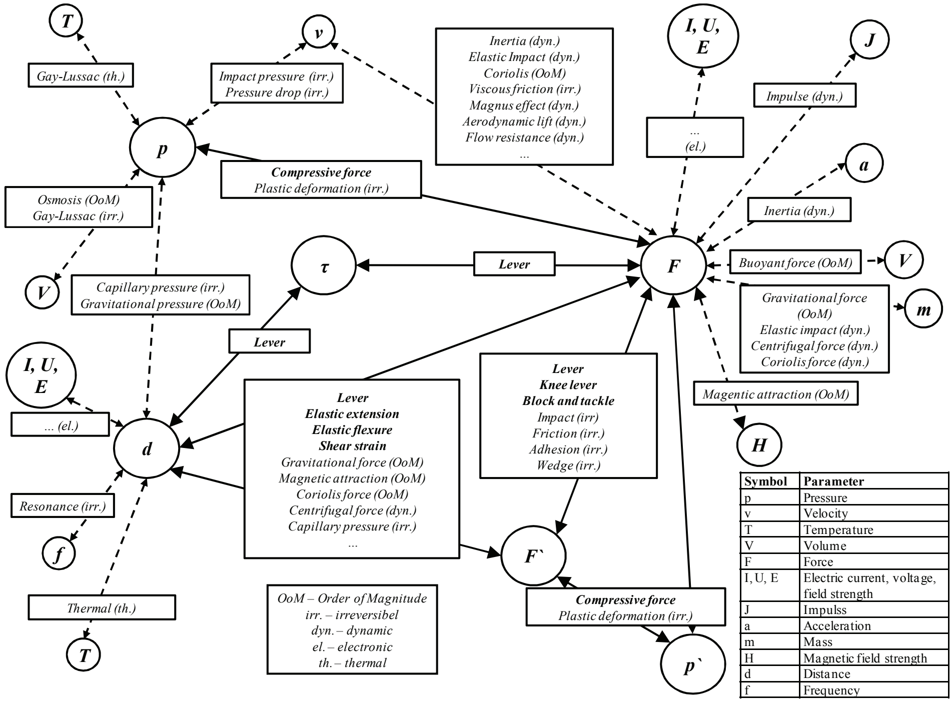


Figure 5. Graph representation of solution space on physical level of abstraction

3.3 Extracting the Solutions

After completing the solution space, the graph can now be discussed in the design team and navigated to extract all valid solutions. In reviewing and discussing the dependencies, some effects are likely to get ruled out due to varying reasons like space and cost constraints, while others might be included. As a result, a list of valid solutions, each item in itself a chain of physical effects, is extracted. The solutions can be used in conceptual design, and constitute a starting point for defining system architectures. To the pressure converter, it could be shown that without altering the restricting constraints given in table 1, the scope of possible solutions (bold faced effects in figure 5) is rather limited; however, a new design was conceived but is not discussed herein.

The building procedure presented in this paragraph is summarized in Table 2.

Table 2. Building procedure for a physical effects network

Step #	**Description**
1	Define start and end parameter
2	Define constraints on physical effects
3.a	Connect all applicable physical effects to parameter
3.b	Mark all invalid physical effects and pertaining parameters Repeat 3.a and 3.b until all parameters are covered
4	Discuss and extract list of valid physical effect chains

4 EXAMPLES OF USE

In design education, the graph representation can help exemplify the concept of alternative solutions to a design problem. Following through the building procedure in tutorials conveys understanding of constraints, as well as synthesis on a high level of abstraction.

In design of hybrid power trains, several physical effects related to energy conversion, storage and transmission are combined to enhance overall efficiency. Expanding on a physical effects network as presented herein, alternative architectures can be derived and examined more closely. In [9], a similar approach is presented, that uses a database of energy-related physical effects and interconnects their specific energy type with the help of matrices. A graph representation to these matrix-dependent effect chains could help in reviewing, discussing and communicating new ideas.

Design Structure Matrices (DSM) and Domain Mapping Matrices (DMM) constitute a less intuitive, but better computable representation of the information contained within graphs. In order to transform the graph representation proposed in this paper into design structure matrices, a modification has to be made. Each physical effect must be understood as a single node which connects two parameters; thereby dispersing the summarized lists of physical effects as in Figure 5 into many independent connections. An example can be found in [10]; therein, physical effects are displayed in a graph that comprises the solution space for energy recuperation in power trains. The resulting, tool-based graph depiction is given in Figure 6.

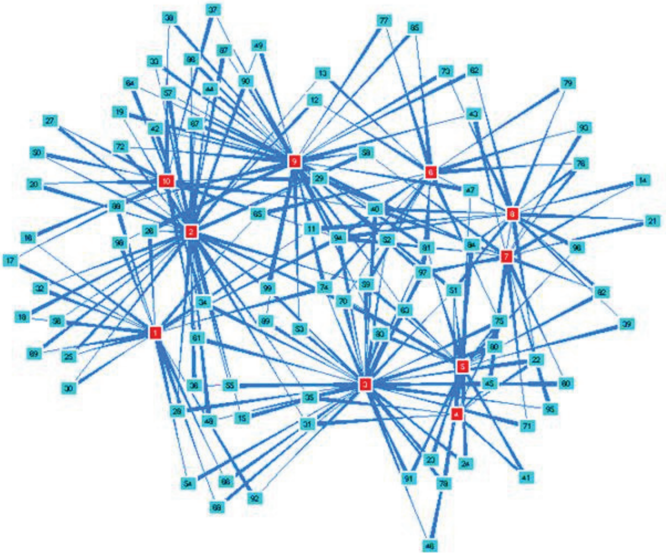


Figure 6. Tool-based graph depiction of a solution space

An obstacle to the transformation of the physical effects networks presented herein to the DSM / DMM methodology lies within ambiguous attributions, e.g. that some physical effects can link many parameters, but that to each pair a different set of constraints may apply. A desired, unambiguous matrix representation would specify a set of attributes to each pair of parameters linked by a specific physical effect. In [11], an approach is introduced that can potentially specify edges in parameter-parameter DSMs by adding further DMMs. This would extend the matrix methodology so as to be computable in respect to many different attributes at once. For instance, energy efficiency and weight of alternative solutions could be compared within one DMM representation.

Future application of the proposed graph representation to actual design problems will yield a list of constraints. A database could then be generated that encompasses a list of physical effects and attributes of all potential linked pairs of parameters as well as a set of constraints. If then a start and end parameter was to be defined, the physical effects network could be built up automatically. This would greatly speed up idea generation, and if combined with analysis criteria for complex structures, could possibly prepare evaluation.

5 CONCLUSION

The paper has proposed a graph representation of physical effects networks to support idea creation in early phases of conceptual design. As input, physical start and end parameters to a given design problem are needed, as well as constraints and requirements. The approach results in a list of possible chains of physical effects.

A proceeding for the building of physical effects networks was presented, putting forward a set of rules for the definition of physical effects networks; physical parameters linked by physical effects with matching in- and output parameters are decomposed, interconnected and integrated to form a network.

By following through the building procedure presented in this paper, graph representations of physical effects networks can be established and used in conceptual design. With the help of constraints that can potentially stem from lists of requirements, a confined network can be built. It represents a valid solution space to a design problem, and allows for the intuitive understanding, discussion within the design-team and communication amongst engineers. A list of valid chains of physical effects can easily be extracted from the graph.

One example of use has been followed through and others have been outlined. It has further been elaborated on how to transfer the graph to the DSM/DMM representation, supported methodology and existing tools. It was shown, that by expanding the methodology to incorporate attributes of single edges and avoiding ambiguity, the approach can be used to automatically retrieve lists of valid chains of effects.

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