Design Science

A multipole-based effect catalog system for the systematic identification of potential measurands

Gunnar Vorwerk-Handing [ID], Peter Welzbacher [ID] and Eckhard Kirchner [ID]

Technical University of Darmstadt, Institute for Product Development and Machine Elements (PMD), Darmstadt, Germany

Abstract

Caused by the progressing digitalization in mechanical engineering, a significant demand for information about characteristic process and state variables of technical systems arises. However, since it is oftentimes neither obvious what nor how to measure, the integration of measuring functions, in particular in terms of a retrofit, represents a current challenge in mechanical engineering. In order to overcome this challenge, an approach for the systematic identification of potential measurands is provided in this contribution. For this purpose, the approach of physical effect catalogs is taken up and used for the systematic identification of potential measurands, starting from a physical variable to be determined. Existing catalog systems have two major limitations with respect to the intended identification of cause–effect relationships: They assume an effect to be realized and a consideration of design parameters of a technical system is not intended. These limitations are overcome by linking the fundamental idea of existing catalog systems with the basics of multipole-based modeling. In this way, a multipole-based effect catalog system is developed. It creates the foundation to systematically include the changes and transformations of a process or state variable to be determined into the identification of potential measurands.

Keywords: Measurands, Measuring function, Retrofit, Multipole-based modeling, Physical effect catalog

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1. Introduction and motivation

The availability of reliable information about processes within and states of technical systems is essential for achieving the vision "Industry 4.0", e.g., to enable predictive maintenance and digital twins [cf. e.g. Schirra *et al.* 2018; Matt & Rauch 2020]. In this context, the term "technical system" covers a wide range from entire (production) plants and machines to assemblies and their components, such as machine elements [cf. Pahl *et al.* 2007]. The demand for information results in additional requirements for these systems that exceed the ones characterizing their primary functions – system-specific process or state variables must be measured.

Depending on the individual branch of industry, the statistical average age of German machinery is between 12 and 18 years. In the USA, the statistical average age is around 10 years. However, from a technical point of view, the machines are even two to three years older than that due to the required development time

[cf. Guerreiro *et al.* 2018]. Accordingly, it can be stated that many technical systems existing today – especially those with long life cycles – were not developed against today's background. Consequently, these machines are unable to provide information about relevant process or state variables. Since replacing every outdated machine is barely realistic in short term and medium term, but also uneconomical, retrofitting of measurement functions comes to the fore.

Since new requirements are involved when retrofitting measuring functions into existing systems, the "Guideline Sensors for Industrie [sic] 4.0" of the German Engineering Federation emphasizes the importance of a solution-neutral discussion of potential measurands [cf. Fleischer *et al.* 2018]. However, the question of potential measurands arises regardless of whether the integration of a measuring function is carried out in form of a retrofit or in the context of a new sensory development. In both cases, the aim is to obtain defined information.

The overall objective when integrating measuring functions is to provide reliable information about processes or states in (existing) technical systems effectively and efficiently. Against this background, this contribution presents an approach developed by Vorwerk-Handing (2021) to systematically establish a relationship between a system-specific state or process variable to be determined and potential measurands. In the approach, physical effects are used and the (existing) technical system as well as its properties is taken into account, the latter in contrast to Helms, Schultheiss & Shea (2013). Therefore, the fundamental approach of using physical effect catalogs is taken up and transferred to the considered context. To overcome the limitations identified in the application of the approach, a new catalog system – so-called multipole-based effect catalog system – was developed by Vorwerk-Handing (2021) in order to provide a basis for the solution-neutral identification and discussion of potential measurands. In the following, a translated summary of the main research results of Vorwerk-Handing (2021) and a presentation of research thematically connected to it is provided.

The remaining contribution is structured as follows: In Section 2, the relevant fundamentals of this contribution are outlined. In Section 3, the aims of this contribution but also its significance are described. The structure and approach for the multipole-based effect catalog system are explained in Section 4. In Section 5, a brief assessment of the results is described. The contribution ends with Section 6, which provides a conclusion and an outlook.

2. Fundamentals

In literature, the development of (retrofit) solutions for the integration of measuring functions into technical systems is oftentimes described in form of process models [cf. e.g. Fleischer *et al.* 2018; Hausmann *et al.* 2023]. An essential step therein is typically the "definition of potential measurands". This is due to the circumstance, that both – direct as well as indirect measurements – are in principle conceivable for measuring physical quantities in a technical system [cf. Regtien 2005; Bureau international des poids et mesures 2008]. Thus, to ensure a uniform understanding, a distinction is made in the following between the state or process variable to be determined and the actual measurand. The process or state variable to be determined is the actual target of the measurement and the subsequent evaluation of the obtained data [cf. e.g. Regtien 2005]. A measurand is defined,

according to the Joint Committee for Guides in Metrology (JCGM), as the "quantity intended to be measured" and thus is the input variable of the sensor [cf. Bureau international des poids et mesures 2012].

In this section, the fundamentals for the methodical establishment of a relationship between a system-specific process or state variable to be determined and potential measurands are described. This includes not only the modeling of measurements based on physical effects but also physical effect catalogs as well as existing approaches for the multidisciplinary modeling of technical systems.

2.1. Modeling of measurements

Measurements, that is the acquisition and representation of physical quantities and the assignment of their corresponding values, are subject of the interdisciplinary field of metrology [cf. Bureau international des poids et mesures 2012]. The structure of an abstracted measurement system is shown in Figure 1, whereby the contents of this contribution are located in the measuring transducer.

Sensors change or convert a physical, chemical or biological measurand into an output signal – nowadays usually an electrical signal. Hence, a sensor can be defined as a device that receives the measurand as input and generates a conditioned electrical signal as output. [cf. e.g. Regtien 2005; Wilson 2005; Kalantar-zadeh & Fry 2008].

Since a sensor in general changes a signal, a measurement can be considered as a recording of the effect X_1 of a cause Y (measurand). The relationship between these two variables is built using physical effects and described by the function h, cf. Figure 2. Besides these two variables, the function h typically includes other variables, such as design parameters, which are designated as $X_2, X_3, …, X_N$. Influences not taken into account in the function h or modeling imperfections, e.g. regarding the measuring object, its environment or the measuring device, cause uncertainty. [cf. Bureau international des poids et mesures 2008; Kreye, Goh & Newnes 2011].

The goal of a measurement is to conclude from the measured effect X_1 to the initial cause Y. This is done via the so-called *model of evaluation*, which is described by the function f [cf. Bureau international des poids et mesures 2008]. The function f is obtained by rearranging the function h according to the searched variable, the measurand Y.

2.2. Physical effects

The relationship between the input and output quantities of a technical system – in terms of its function – is established by *physical, chemical and/or biological effects* [cf. e.g. Pahl *et al.* 2007; Mokhtarian, Coatanéa & Paris 2017]. Accordingly, a function of a technical system can be described by means of the utilized effects. In mechanical engineering, the aforementioned relationship usually comes about as a result of a physical effect or the linkage of several physical effects [cf. e.g. Hansen & Andreasen 2002; Pahl *et al.* 2007; Stetter 2020].

A physical phenomenon or event is defined as *physical effect*, whereby the corresponding quantitative relationship between the involved physical quantities is referred to as *physical law*. Since physical effects enable the fulfillment of functions, their consideration represents an established approach when aiming for a function
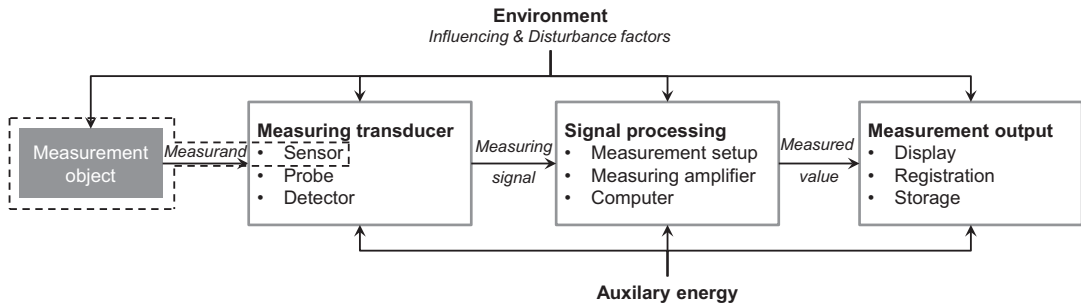
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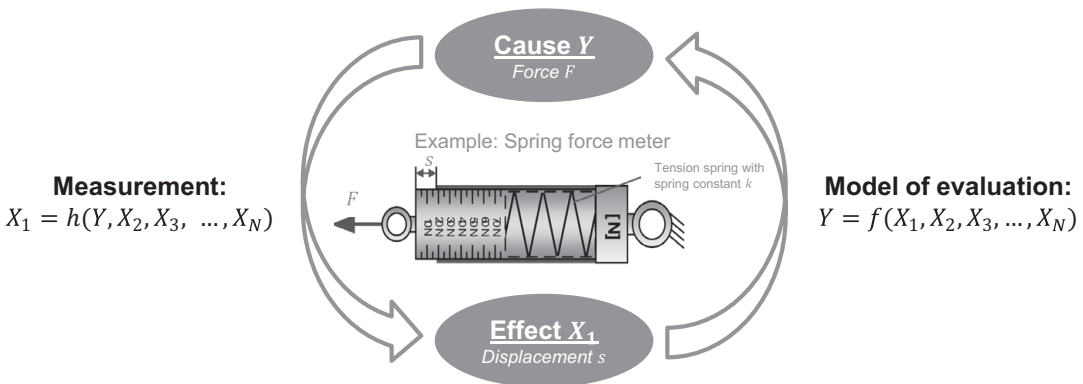**Figure 1.** Structure of an abstracted measurement system [translated from Czichos 2019].

Figure 2. Development of a model of evaluation based on a cause–effect relationship [cf. Harder *et al.* 2021; based on Wilson 2005 and Weckenmann, Sommer & Siebert 2006].

to be realized. The technical realization of a physical effect takes place through a geometric-material structure – so-called *working geometry* – in a defined environment, that is in the technical system. In this context, the link between physical effect and working geometry is referred to as the *working interrelationship*. The necessary conditions of a technical system to realize a physical effect can be described by the geometric, material and kinematic properties of the system. Figure 3 illustrates the different terms, using the example of a mechanical lever. [cf. Finkelstein, El-hami & Ginger 1998; Pahl *et al.* 2007; Stetter 2020].

2.3. Physical effect catalogs

For the development of technical systems, the availability of information at a specific point in time is an elementary prerequisite. However, a considerable proportion of (generally) acquired knowledge cannot be applied usefully, because it is generally not available or not available in a suitable form. This applies in particular to developers who permanently rely on physical, technological or material knowledge. As soon as the information available in the developers' memory is no longer sufficient, access to externally stored knowledge or information is required [cf. Savransky 2000]. Therefore, design catalogs can be used as tools to improve the availability and utilization of existing knowledge and consequently
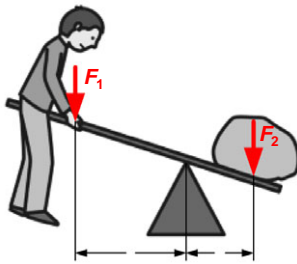
General function:
Change (and channel)

Physical effect:
Leverage effect

Physical law:
$F_2 = F_1 \cdot \dfrac{l_1}{l_2}$

Implementation in the technical system by means of a working geometry:
Beam and support

Properties of the technical system:
Geometric: length l_1 and l_2, geometric moment of inertia of the beam I
Material: Elastic modulus of the beam material E
Kinematic: Coupling between beam and support with one rotational degree of freedom

Figure 3. Realization of a function in a technical system based on a physical effect [translated from Vorwerk-Handing 2021].

as suitable means for better solutions. [cf. e.g. Verein Deutscher Ingenieure 1982; Koller 1998; Helms *et al.* 2013; Ehrlenspiel & Meerkamm 2017].

According to VDI 2222 – Sheet 2, the generic term *design catalog* covers information and knowledge repositories that are tailored to the methodical development of technical systems in terms of their content, access features and structure. Design catalogs are characterized by extensive completeness, access features as well as a clear system and structure. Design catalogs are further distinguished into three types:
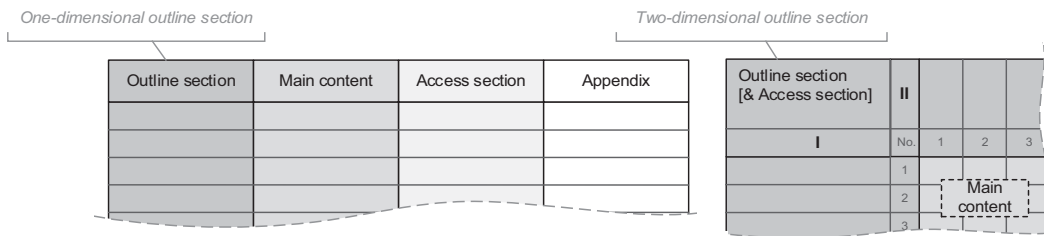
- object catalogs,
- operation catalogs and
- *solution catalogs* [cf. Verein Deutscher Ingenieure 1982].

Since object catalogs contain task-independent information necessary for development, especially from the field of physics, they come to the fore at this point. Object catalogs that contain information about physical effects are designated as *physical effect catalogs*. These catalogs differ from mere collections of physical effects, e.g., the one from Young & Freedman (2016), in terms of access features. [cf. Verein Deutscher Ingenieure, 1982].

Since physical effects generally establish a relationship between two physical quantities, effect catalogs are structured accordingly, based on the cause–effect principle of the involved quantities [cf. e.g. Koller 1998; Roth 2000; Ehrlenspiel & Meerkamm 2017]. Similar to the structure of design catalogs, physical effect catalogs consist of an *outline section*, a *main content* and an *access section* – including an *appendix*, if applicable. Depending on the number of physical quantities involved in the structuring of an effect catalog, a distinction is made between one-, two- or three-dimensional catalogs. The fundamental structure of effect catalogs and the distinctions introduced are illustrated in Figure 4.

The structure of existing effect catalogs as well as their respective inclusion in a procedure for the synthesis of principle solutions differs in detail depending on the author [cf. Helms *et al.* 2013]. The most widespread catalog systems are the one by Koller (1998) and the function variable matrix by Roth (2000). These two systems serve as references in the following.

At this point, it should be noted that besides analog catalog systems, there are also digital systems in the form of *effect databases*. An example of such a database is the one by Oxford Creativity Ltd. (n.d.) or the SAPPhIRE database by Srinivasan &

Figure 4. Structure of physical effect catalogs with a one- or two-dimensional outline section [translated from Vorwerk-Handing 2021; based on Koller 1998 and Roth 2000].

Chakrabarti (2011). Effect databases are oftentimes referred to in the "Theory of Inventive Problem Solving" (TRIZ). Since it is not possible to derive generally valid statements from existing effect databases due to a lack of available information about their completeness as well as underlying structure and logic, their significance for this contribution is rated low and they are neglected in the following. In perspective, however, the computer-based implementation of the results of this contribution in the form of an effect database is conceivable and worthwhile.

2.4. Multidisciplinary modeling of technical systems

Mechatronic systems typically consist of a basic system, sensors, actuators and an information processing unit [cf. e.g. Verein Deutscher Ingenieure 2021]. Qualitative system models make it possible to structure such a system in a way that it is understandable for the developer and the inner relationships become apparent [cf. e.g. Mokhtarian *et al.* 2017]. On this basis, design variants can be developed. Furthermore, the qualitative modeling of the system enables the subsequent quantitative modeling of clearly defined and manageable subsystems in form of mathematical equations [Janschek 2012]. In general, two approaches can be used to model mechatronic systems:

- On the one hand, according to the "*domain-specific design*" described in the V-model, they can be modeled from the point of view of the involved disciplines – mechanical, electrical and software engineering [cf. Verein Deutscher Ingenieure 2021].
- On the other hand, a domain-independent modeling of the entire system can be done [cf. Janschek 2012].

Since the former contradicts the cross-domain modeling required for a systematic identification of potential measurands, domain-independent multipole-based modeling is chosen. The structure of a multipole-based network model allows to obtain the physical topology of the considered system. This offers the possibility to modularize models – or the modeling process in general – on the basis of an explicit technical component assignment. In addition, the multipole-based modeling approach is also suitable for complex systems [cf. Janschek 2012].

In multipole-based modeling, systems with a multidisciplinary character are described uniformly on the basis of lumped parameter network elements and general energy conservation laws. The linkage of the spatially and functionally delimited network elements to an overall system model takes place via terminals, ports, respectively, based on power-conservation interconnection laws (Kirchhoff's
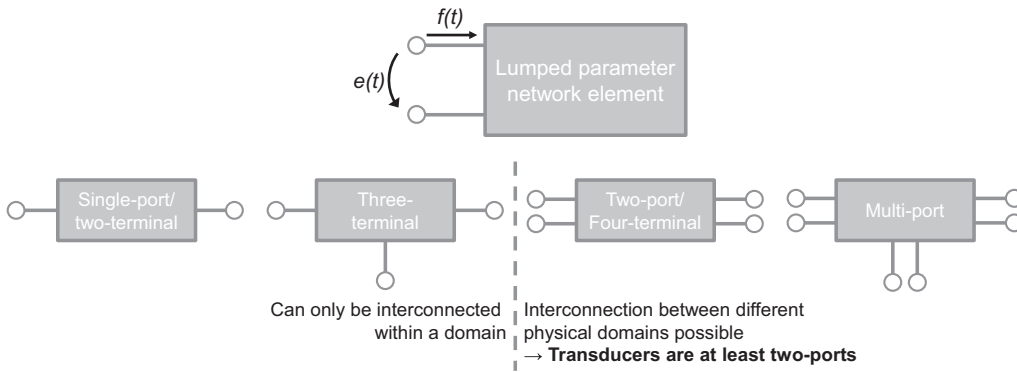
Figure 5. Overview of different types of lumped network elements [translated from Vorwerk-Handing 2021; based on Janschek 2012].

laws). Based on the number of terminals, network elements are distinguished into two terminal or single ports, three terminal, four terminal or two ports or multi-ports, cf. Figure 5. [cf. e.g. Janschek 2012].

The basis of multipole-based modeling is the *energy exchange* between the network elements by means of a pair of conjugated *generalized energy variables* or *terminal variables* [cf. e.g. MacFarlane 1964; Wellstead 1979; Janschek 2012]. These are defined as

- generalized effort variable *e* and
- generalized flow variable *f*.

Examples of generalized effort variables are the velocity v or the electric voltage U, whereas examples of generalized flow variables are the force F or the electric current I.[1] The product of the domain-specific effort and flow variable is power $P(t)$, cf. equation 1 [cf. e.g. MacFarlane 1964; Wellstead 1979; Janschek 2012].

$$P(t) := e(t) \cdot f(t) \tag{1}$$

Since the pair of generalized energy variables describes the energy exchange, but not the energy stored within the system or element, these two quantities are not sufficient to describe the total energy of a system or element. The *total energy* in a closed system or element can be described by *fundamental variables*. Since energy, as a quantity-like physical state variable, cannot flow alone, it always requires an energy carrier. Each energy carrier in turn has a potential [cf. Wellstead 1979]. The already introduced generalized energy variables e and f are not dependent on the size of the system or a quantity in general. For this reason, they are designated as *intensive state variables* or *intensity variables* i_j. Examples of intensive state variables are the force F, the electric current I, the velocity v or the electric voltage U. In contrast, state variables that are dependent on the size of the considered system or generally a quantity are called *extensive state variables* q_j. Examples of extensive state variables are the momentum p, the electric charge Q, the

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[1]In literature, opposing classifications are described under the assumption of a different point of view. The viewpoint introduced at this point will be maintained for the remainder of this contribution. Further information can be found in Wellstead (1979) as well as Janschek (2012).

displacement *s* or the induction flux Φ. Intensive and extensive state variables are linked according to equation 2.

$$i_j := \frac{dq_j}{dt} \tag{2}$$

According to Gibb's fundamental form for equilibrium states, the energy change of a system is calculated according to equation 3.

$$\delta E = \sum_j i_j \cdot \delta q_j \tag{3}$$

According to equation 3, the total energy of a system or an element results from the sum of the products of the two pairwise intensive and extensive state variables [cf. Wellstead 1979]. Hence, within a physical domain, exactly four system variables can always be formed, two intensive variables and two extensive variables. The two intensive variables and extensive variables can further be distinguished based on their metrological properties:

- State variables, for whose determination only one point in space is required, are designated as *P-variables* (from Latin *per* – "through") or *single-point variables*. They are denominated with the index P. Examples for P-variables are the force *F*, the electric current *I*, the momentum *p* or the electric charge *Q*.
- State variables, for whose determination two points in space are required, are designated as *T-variables* (from Latin *trans* – "over") or *two-point variables*. They are denominated with the index T. Examples for T-variables are the velocity *v*, the electric voltage *U*, the displacement *s* or the induction flux Φ.

The definitions and relationships described above are summarized in Table 1. The already mentioned examples from the domains of mechanics and electricity are taken up consistently in this table as well as in Table 2 and in Figure 6.

The introduced system variables are linked by two types of *constitutive laws*. The *temporal relationship* between intensive and extensive state variables has already been introduced in equation 2. The relationship between P- and T-variables is established via *design parameters*. These design parameters cause either storing (e.g., spring constant *k* or electric capacity *C*) or transforming (e.g., internal damping *d* or electrical resistance *R*) properties on the systems' level. The different constitutive laws are summarized in Table 2.

An overview of the system variables, their laws of formation and their linkage by constitutive laws is shown in Figure 6. It apparent, starting from the primary variable *X*, that the other three system variables can be derived unambiguously, at least mathematically. In practice, however, it is not always trivial to set up the cross-domain analogy relationships in the correct way [cf. Janschek 2012].

3. Aims and significance

The integration of measurement functions into existing technical systems is one of the current challenges in mechanical engineering. This is of great importance and topicality, especially against the background of "Industry 4.0" and predictive maintenance. To avoid an early unfounded restriction of the solution space by a prefixation and thus impede innovative or promising solutions, the importance of a solution-neutral discussion of potential measurands is emphasized in

Table 1. Summary of system variables in the context of multipole-based modeling [translated from Vorwerk-Handing 2021; Janschek 2012]

System variable	Symbol	Property	Energy variable	Power variable	Examples (Mechanics/ electricity)
Primary variable	X	P-variable Extensive state variable	q_P	–	Momentum p/ Electric charge Q
Effort variable	Y	T-variable Intensive state variable	i_T	e	Velocity v/ Electric voltage U
Flow variable	I_M	P-variable Intensive state variable	i_P	f	Force F/ Electric current I
Extensum	Ex	T-variable Extensive state variable	q_T	–	Displacement s/ Induction flow Φ

Note:
P-variable ≙ one-point variable extensive state variable ≙ „quantity"
T-variable ≙ two-point variable intensive state variable ≙ „intensity"

Table 2. Overview of the constitutive laws for the linkage of system variables [translated from Vorwerk-Handing 2021]

Description	Equation (definition)	General element	Property	Example (Mechanics/electricity)
Capacitive law	$C := \frac{q_P}{i_T}$	Capacity	Energy storage	Mass m / Capacity C
Resistive law	$R := \frac{i_T}{i_P}$	Resistance	Energy converter	Internal damping d / Electrical resistance R
Inductive law	$L := \frac{q_T}{i_P}$	Inductivity	Energy storage	Spring constant k / Inductivity L
Memristive law	$M := \frac{q_T}{q_P}$	Memristor	Energy converter	–

literature [cf. e.g. Fleischer *et al.* 2018]. Hence, the users' creativity is stimulated, mental blocks are dissolved and innovative solutions are enhanced [cf. Zavbi & Duhovnik 2001; Srinivasan & Chakrabarti 2011; Stetter 2020]. However, no systematic approach to establish relationships between a state or process variable to be determined and potential measurands, taking an existing system into account, could be found in literature [cf. Vorwerk-Handing 2021; Hausmann *et al.* 2023].

This chapter is structured as follows: In Section 3.1, potentials and limitations of existing effect catalogs are discussed. Based on the outcome of this discussion, the objective and research design are described in Section 3.2.
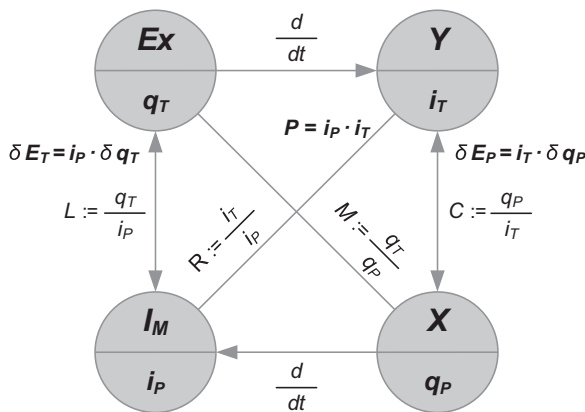
Figure 6. Overview of the system variables and their linkage by constitutive laws [based on Paynter 1961].

3.1. Potentials and limitations of existing effect catalogs

Since physical effects in general establish a relationship between different physical quantities, effect catalogs are used to systematically establish relationships between process or state variables to be determined and potential measurands. In the intended context, the application of existing effect catalogs is in principle permissible. However, the previously considered main representatives of analog effect catalogs, Koller (1998) and Roth (2000), were originally developed to find working principles for (sub-)functions to be realized [cf. Pahl *et al.* 2007]. Hence, the original purpose of these catalogs is to establish a relationship between a sought for effect and causes that could potentially be used for the intended purpose. As a result, there are two major limitations to the identification of cause–effect relationships by means of existing effect catalogs:

- Existing effect catalogs assume an effect to be realized. Due to the irreversibility of some physical effects, an inverse application of existing catalogs is not permissible.
- According to the original purpose of effect catalogs, a consideration of design information is not intended. With regard to the intended consideration of existing systems, it is stated that the inclusion of the design of an existing technical system is not sufficiently supported.

As a result, not all usable relationships between system-specific process or state variables and potential measurands can be mapped systematically using existing effect catalogs. Since the effect catalogs by Koller (1998) and Roth (2000) differ in particular in terms of structuring and content, more detailed restrictions were elaborated in Vorwerk-Handing (2021).

3.2. Objective and research design

The main objective is the systematic establishment of relationships between a system-specific process or state variable and potential measurands to realize a sought for measuring function. The technical system into which the measuring

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function is to be integrated is considered by modeling on the level of physical effects using an effect matrix and the associated effect catalog.

As basis for the conception and development of an effect matrix and the associated effect catalog, requirements and boundary conditions are collected and defined. The requirements are based on the analysis of the problem-related limitations of existing catalog systems and are completed in accordance with VDI 2222 – Sheet 2 [Verein Deutscher Ingenieure 1982]. To develop a catalog system that meets these requirements, Vorwerk-Handing (2021) took up the fundamental idea of the effect catalogs by Koller (1998) and Roth (2000) and combined it with the fundamentals of multipole-based modeling. Thus, the chosen approach provides a basis for the systematic identification of potential measurands while taking an existing technical system into account.

4. Multipole-based effect catalog system

In order to systematically establish relationships between a system-specific process or state variable and potential measurands, a catalog system consisting of an effect matrix and an associated effect catalog was developed by Vorwerk-Handing (2021). For the development of this catalog system, the fundamental idea of the catalog systems by Koller (1998) and Roth (2000) is taken up and combined with the fundamentals of multipole-based modeling. According to the intended purpose, a cause–effect perspective is consistently applied. This results in a physically and logically justified structure of the developed catalog system.

The overall objective of the developed catalog system is to establish relationships between a system-specific process or state variable and potential measurands. This is achieved by linking several physical effects and thus forms a so-called effect chain. Generalized relationships between a cause and a resulting effect are systematically built and mapped in the two-dimensional effect matrix. Information about the respective physical effects that establish these relationships is stored in the one-dimensional effect catalog.

To ensure that the generated effect chains are metrologically usable with respect to the accuracy that can be achieved with them, an uncertainty analysis has to be conducted. Since the focus in this contribution is on the multipole-based effect catalog system, the topic of uncertainty analysis is not included in this contribution. For a detailed description of the uncertainty analysis including various application examples, it is referred to Vorwerk-Handing, Welzbacher & Kirchner (2020) and Vorwerk-Handing (2021).

This chapter is structured as follows: The two-dimensional effect matrix of the catalog system and its structuring are described in Section 4.1. The associated one-dimensional effect catalog is described in terms of its main content and access section in Section 4.2.

4.1. Effect matrix

The two-dimensional overview catalog of the catalog system is structured in the form of a matrix, designated as effect matrix, which is schematically shown in Figure 7. The matrix lists the causes in columns and the resulting effects in rows. Since the effect matrix serves as an overview catalog, the approach described in the
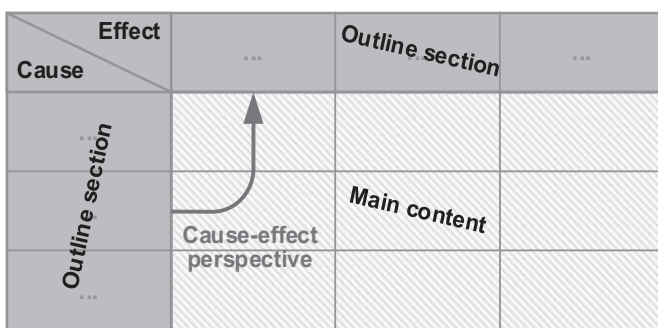
Figure 7. Schematic structure of the effect matrix [Harder *et al.* 2021].

following and the resulting structure of the effect matrix represent the main outcome of this section.

4.1.1. *Fundamental approach for structuring the effect matrix*

The causes and effects in the outline section of the matrix are structured according to the *main domains of* classical physics in *mechanics*, *electricity* and *magnetism* as well as *thermodynamics* [cf. Hering, Martin & Stohrer 2016]. The field of periodic changes in state is considered in the domain's mechanics (matter-bound waves, e.g., fluid sound) and electricity and magnetism (non-matter-bound waves, e.g., light).

The physical variables listed in the outline section are derived from the eight *quantities of physics that can be balanced.* The general balancing of energy forms the basis for this. For a differentiated classification, the other seven balanceable quantities of classical physics are used: translational momentum p, angular momentum L, (heavy) mass m_S, volume V, electric charge Q, entropy S and amount of substance n [cf. Maurer 2015]. According to the basics of system variables introduced in Section 2.4, the seven balanceable quantities are used as primary variables X. The respective flow and effort variables I_M and Y as well as the extensum E_X are mathematically derived from the primary variables X. The approach to structure the effect matrix is schematically shown in Figure 8. Figure 10 shows an extract of the outline section using the example of translational momentum p and electric charge Q.

The resulting structure and compatibility with multipole-based modeling bring other advantages:

- Based on the differentiation of system variables, it is possible to draw a direct conclusion on the metrological properties of the quantities. According to Section 2.4, the four system variables of a physical domain can be distinguished into *P-variables* (single-point variables) and *T-variables* (two-point variables).
- Since the energy exchange between different network elements within a multipole-based model can always be described by the flow and effort variable of the involved physical domains, energy flows and thus the changes and transformations of a function variable in a system can be modeled [cf. Janschek 2012].

  ○ In this way, it is possible to structure the system step by step along nodes, e.g., based on flow variables, and to model it sequentially [cf. e.g. Vorwerk-
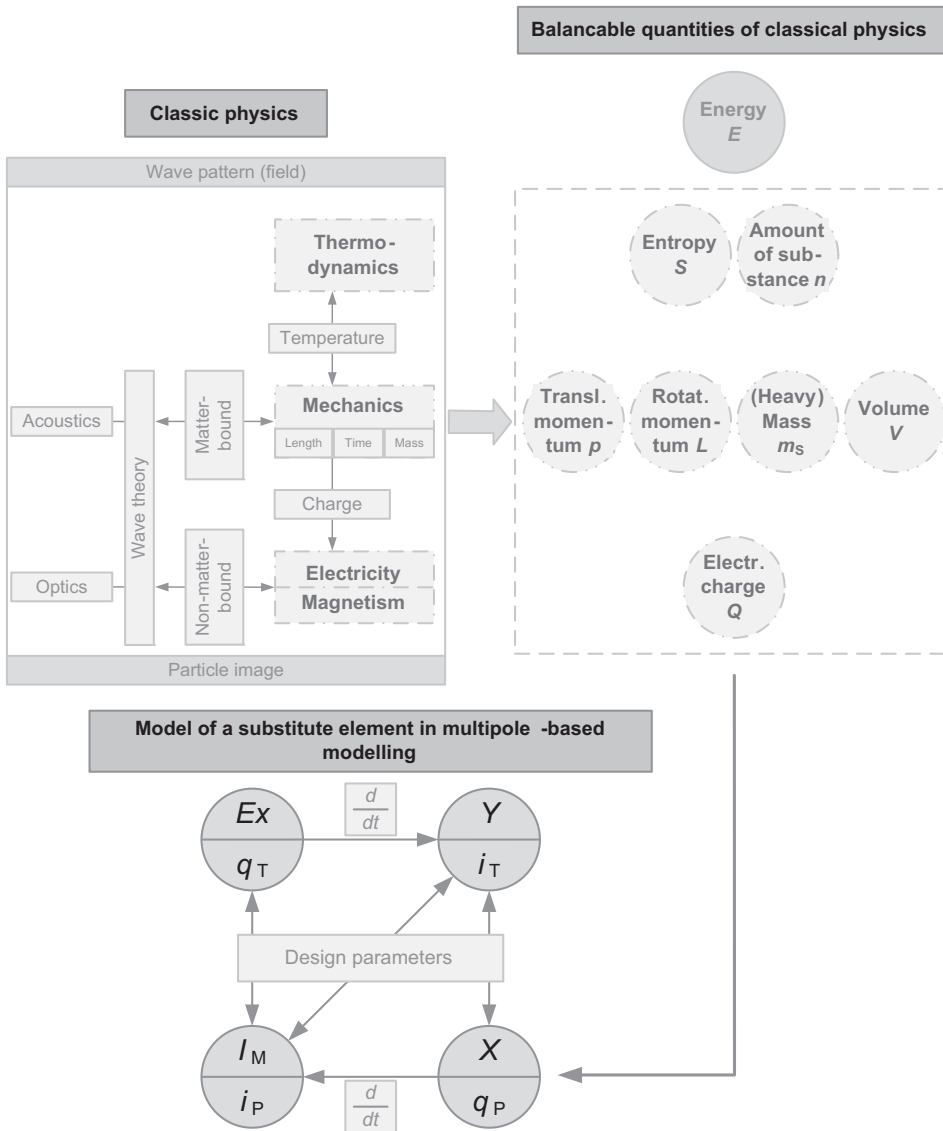
Figure 8. Overview of the approach to structure the effect matrix [translated from Vorwerk-Handing 2021; upper left – physical domains from Hering *et al.* 2016].

Handing, Martin & Kirchner 2018]. The term "node" goes back to the consideration of the electric current in electrical networks according to Kirchhoff's node rule and can be transferred to other flow variables [cf. e.-g. Borutzky 2010; Janschek 2012]. In mechanics, e.g., this corresponds to the balancing of forces, cf. Figure 9.

○ By the respective effort variables, relationships between discretely modeled substitute elements in a system can be mapped along meshes [cf. MacFarlane 1964]. In electrical networks (cf. Figure 9), this corresponds, e.g., to the
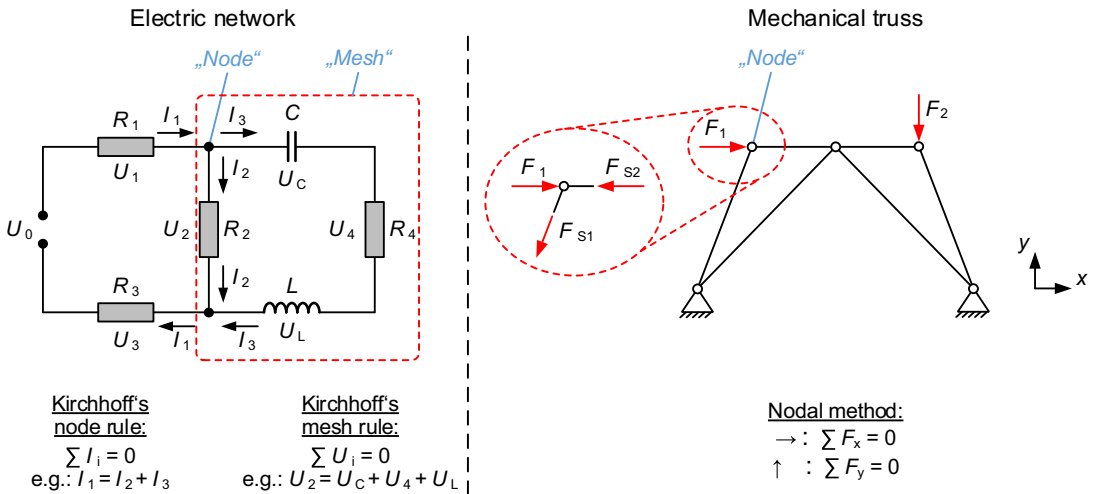
Figure 9. Node and mesh rule according to Kirchhoff in an electrical network (left) and nodal method on a free-cut mechanical truss (right) [translated from Vorwerk-Handing 2021].

consideration of all partial voltages in the circuit of a mesh according to Kirchhoff's mesh rule [cf. e.g. Borutzky 2010; Janschek 2012] (Figure 10).

In multipole-based modeling, the relationships between the four system variables are established either by design parameters or a temporal relationship [cf. e.-g. Janschek 2012]. This is taken into account by including the corresponding design parameters and the time t in the effect matrix. Since the design parameters and the time t establish the relationship between the variables, they cannot occur as a cause in a physical effect and are consequently not listed in the input outline section of the effect matrix. However, since design parameters are influenced by system variables, the design parameters as well as the time t are listed as effects in the output outline section of the effect matrix, cf. Figure 11.

To establish and model relationships between function variables of different physical (sub-) domains, the described structure of the output outline section of the effect matrix is of fundamental importance for two reasons:

- Design parameters not only built a relationship between system variables within a (sub-)domain, but also *across (sub-)domains.* In the latter case, energy is exchanged between the involved (sub-)domains. An example for a relationship between system variables of different domains is *Coulomb's law.* It describes the force F between two electric charges Q and Q', which are idealized as point charges (cf. Figure 12).

Consequently, a relationship between the *electric primary variable of the charge Q* (cause) and the *flow variable force F* (effect) from the domain of mechanics is described. This relationship is established by the design parameter of the *length*[2] and the vacuum permittivity ε_0 as shown in equation 4 [cf. Janschek 2012].

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[2]The distance r between the two point-shaped charges Q and Q' corresponds to the design parameter length l.
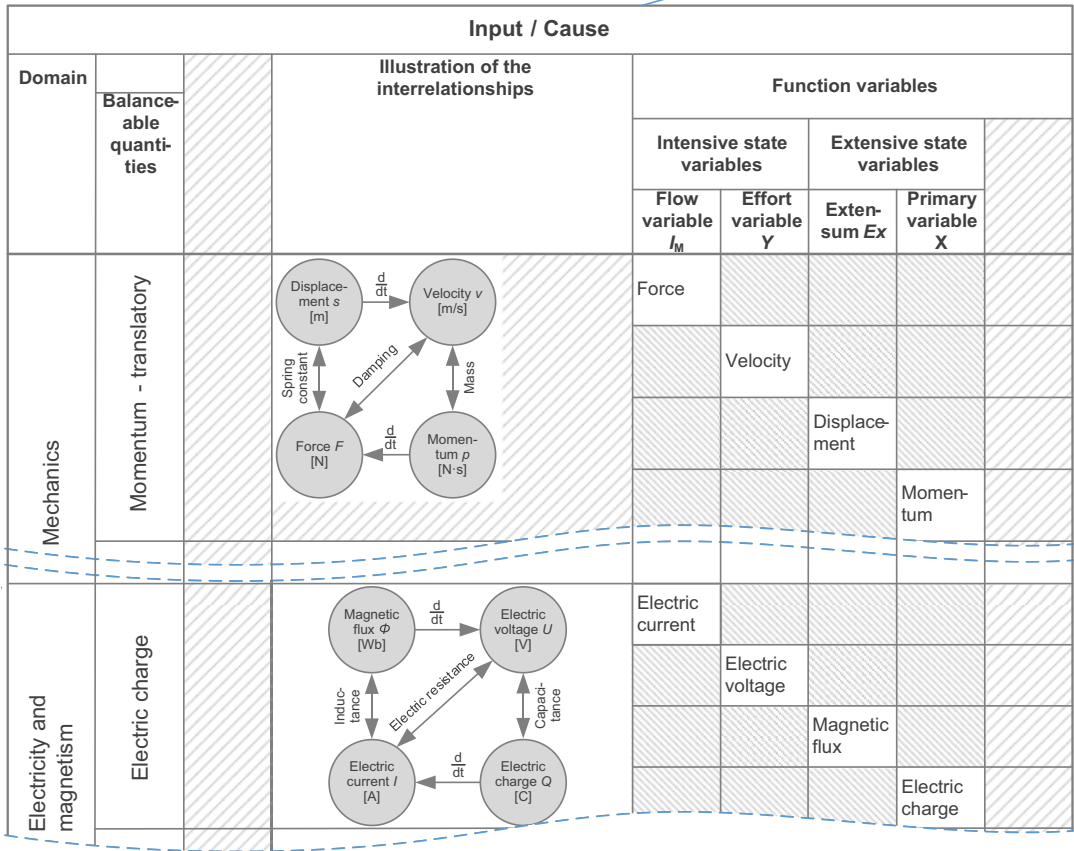
Figure 10. Extract of the outline section of the effect matrix for translational momentum p and the electric charge Q [translated from Vorwerk-Handing 2021].

$$F = \frac{Q \cdot Q'}{4\pi \cdot \varepsilon_0 \cdot r^2} \tag{4}$$

In this context, F is the force emanating from the electric charges Q and Q' and r is the distance between these two charges, which are assumed to be point-shaped.

- Furthermore, design parameters of a (sub-)domain can be influenced by system variables or function variables of other (sub-)domains. In this case, there is almost no energy exchange between the (sub-)domains. By influencing a design parameter, system variables or function variables of one (sub-)domain indirectly influence another (sub-)domain. These relationships can be used metrologically, e.g., in measuring resistors. In a measuring resistor, the design parameter *electrical resistance R* (domain of electricity) is influenced by the thermal function variable *temperature T* (domain of thermodynamics).
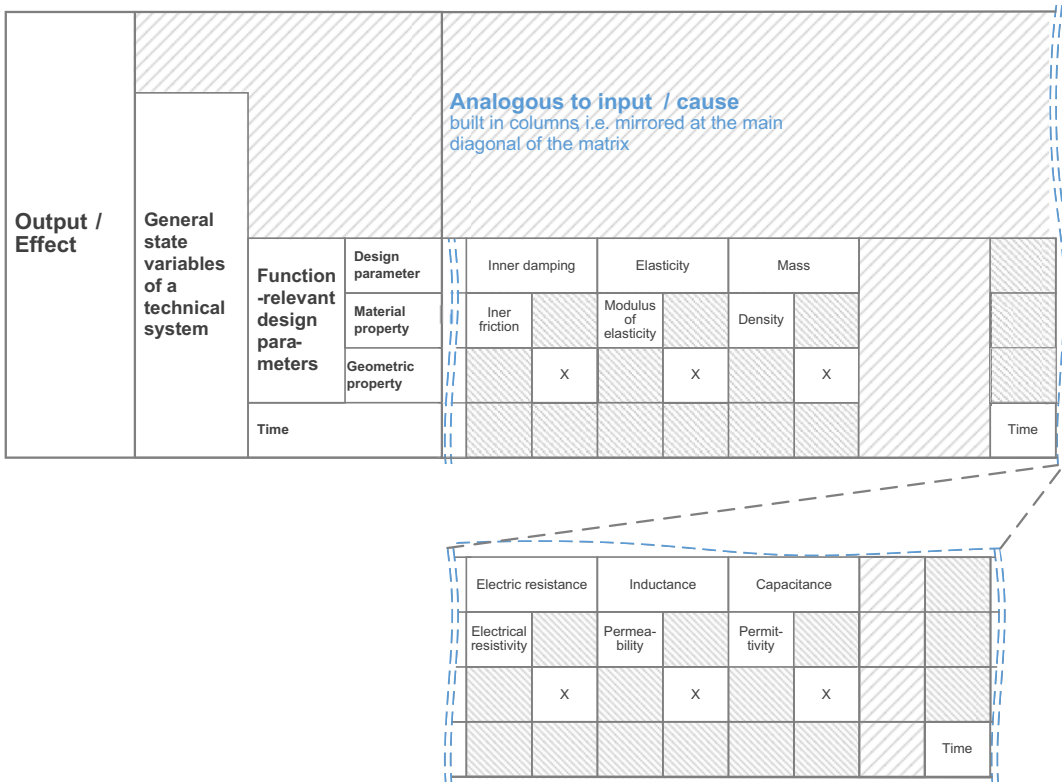
Figure 11. Extract of the output outline section of the effect matrix [translated from Vorwerk-Handing 2021].

In addition, this systematic consideration of design parameters allows for a clear distinction between system variables and design parameters, which is, e.g., not present in the matrix of Koller (1998).

In order to meet the level of abstraction chosen by the user when considering the described relationships, the superordinate design parameters are further differentiated into independent material and geometric properties (cf. Figure 11). The user considers, e.g., Hooke's law that describes a relationship between the force F and the displacement s. Depending on the needs and knowledge of the user, this relationship is established on different observation levels. On the one hand, it is possible to establish the relationship via the spring constant k of the component, which can be directly determined in experiments. On the other hand, in a one-dimensional case, the relationship can be established via the surface area A perpendicular to the force F and the initial length l_0 (geometric properties) as well as the elastic modulus E (material property), cf. Figure 13.

4.1.2. Extensions

The application and comparison of the above described effect matrix with the assignment matrix by Koller (1998) show that it is reasonable and necessary to include also derived variables in the outline section of the matrix. This is mainly
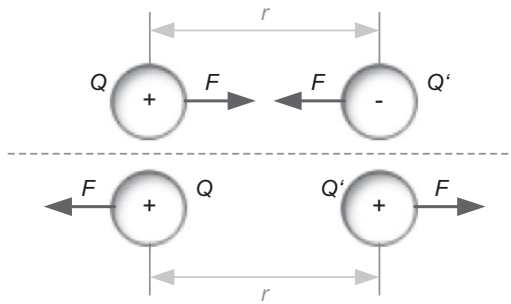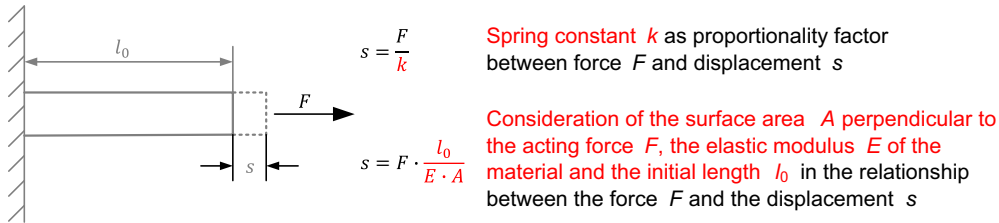
Figure 12. Coulomb's law – Force F between two electric charges Q and Q' [Vorwerk-Handing 2021].

Hooke's law
Displacement s as effect of the cause force F
(Assumptions: linear-elastic behavior, one-dimensional consideration)

$$s = \frac{F}{k}$$

Spring constant k as proportionality factor between force F and displacement s

$$s = F \cdot \frac{l_0}{E \cdot A}$$

Consideration of the surface area A perpendicular to the acting force F, the elastic modulus E of the material and the initial length l_0 in the relationship between the force F and the displacement s

Figure 13. Hooke's law as an example of the dependence of the level of abstraction in the consideration of the described relationship [translated from Vorwerk-Handing 2021].

due to the metrological relevance of some derived variables. The basis for the extension is formed by two essential observations:

- The underlying approaches of systems' physics and multipole-based modeling cannot display some areas of physics that are physically and, in particular, technically relevant.
- Physical variables derived from the variables already listed in the effect matrix sometimes have a wide practical use.

Both aspects will be explained in more detail in the following and, based on this, a pragmatic extension of the approach for structuring the effect matrix is described. The *derived variables* include related variables that are derived from the process and state variables already listed by

- a reference to a design parameter (e.g. mass m, length l or surface area A) or
- a derivation according to the time t, an integration over the time t, respectively.

In this way, electrical and magnetic flow variables are included in the approach in addition to the classically related quantities of mechanics, such as the stress σ or τ or the strain ε. The resulting extensions of the effect matrix are exemplarily shown in Figure 14 for the variables' translational momentum p and electric charge Q.

Figure 14. Extract of the extended outline section of the effect matrix [translated from Vorwerk-Handing 2021].

Since the systems' physics approach and the multipole-based modeling are not suitable to model magnetic effects, an extension of the approach is made. The reason for the described limitation is that the existence of a magnetic monopole or magnetic charge as the counterpart of the electric charge Q is yet to be proven. The necessity of an extension results from the fact that such a magnetic charge would have to be used as a primary variable in order to derive the other three system

Figure 15. Inclusion of magnetic effects in the effect matrix [translated from Vorwerk-Handing 2021].

variables. Since magnetic effects are important from a technical and metrological point of view, they must be taken into account in the effect matrix. Hence, the magnetic variables and relationships shown in Figure 15 are included in the outline section. In order to achieve a representation that is as uniform as possible, the representation of the relationships in Figure 15 is based on the overview representation used in Section 2.4. However, as described, it represents a deliberately defined exception to the basic approach.

Aspects of wave theory (matter-bound and non-matter-bound waves) have to be considered in a differentiated manner in the outline section of the effect matrix. Matter-bound waves, e.g. fluid sound, are considered in the domain of mechanics and non-matter-bound waves, e.g. light, in the domain of electricity and magnetism.

- Matter-bound waves as periodic changes of state can be represented as structure-borne sound by function variables of the translational momentum p or as fluid sound by function variables of the balanceable quantity of the volume V. This differentiation is based on the fact that in fluids only longitudinal waves occur and propagate in the form of pressure and density fluctuations. In most cases, a dynamic field variable, the sound pressure p, is measured to quantify the fluid sound. Kinematic variables, such as the sound velocity v, are rarely measured [cf. e.g. Cremer, Heckl & Petersson 2005]. In solids, on the other hand, shear stresses occur in addition to normal stresses. As a result, both longitudinal waves

and transversal waves occur and propagate independently of each other. In contrast to fluid sound, kinematic variables such as deflection s (i.e. the relative displacement or strain), velocity (speed v) or acceleration a are measured to quantify structure-borne sound. If required, dynamic variables such as stresses and forces are determined indirectly by the derivatives of kinematic variables and corresponding material properties [cf. e.g. Cremer *et al.* 2005].

- Coupled electric and magnetic fields in the form of non-matter-bound electromagnetic waves are considered in the domain of electricity and magnetism by listing their characterizing variables wavelength λ[3] and intensity I.

The complete outline section of the effect matrix including the described extensions can be found in Vorwerk-Handing (2021).

4.2. Effect catalog

The overall objective is to systematically identify effect chains that can be to realize a measuring function in an existing technical system. The effect catalog contains relevant information about the physical effects included in the effect matrix. Of particular relevance is the collection of selection criteria for certain effects that can already be applied at this level of abstraction and the resulting opportunity to develop promising effect chains.

The one-dimensional effect catalog systematically lists information about the physical effects listed in the effect matrix. For this purpose, there is an interface between the effect matrix and the catalog in form of a consistent and unambiguous designation of the physical effects as well as identification numbers for each effect. Since the introduced effect matrix and the effect catalog form a catalog system with a common interface, the structure of the effect catalog's outline section results from the effect matrix [cf. also Vorwerk-Handing 2021]. As shown schematically in Figure 16, the content of the effect catalog is subdivided into main content and access section, which are described in the following.

4.2.1. Main content of the effect catalog

The main content of the effect catalog lists relevant information about the physical effects included in the effect matrix. The basis for the selected information goes back to the catalog system by Koller (1998). Accordingly, a sketch, an example of application and references for further information are listed for each physical effect. In contrast to the catalog system by Koller (1998), The simplifications assumed for each physical effect are not listed in an additional table, but are directly included in the column "*simplifications made*" (cf. Figure 17).

Since the equation for a physical effect, according to Koller (1998) and Roth (2000), is either generally valid and abstract or describes a certain application or characteristic and thus already contains certain assumptions, the column "*characteristic*" is added to the effect catalog, cf. Figure 17. In this column, the principal characteristic(s) of the relationship between cause and effect are qualitatively described, e.g. in bullet points or a graph (cf. Figure 17). In this way, it is

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[3]The wavelength λ can also be expressed by means of the media-dependent phase velocity c_{med} and the frequency f. The relationship is established by $\lambda = \frac{c_{\mathrm{med}}}{f}$.
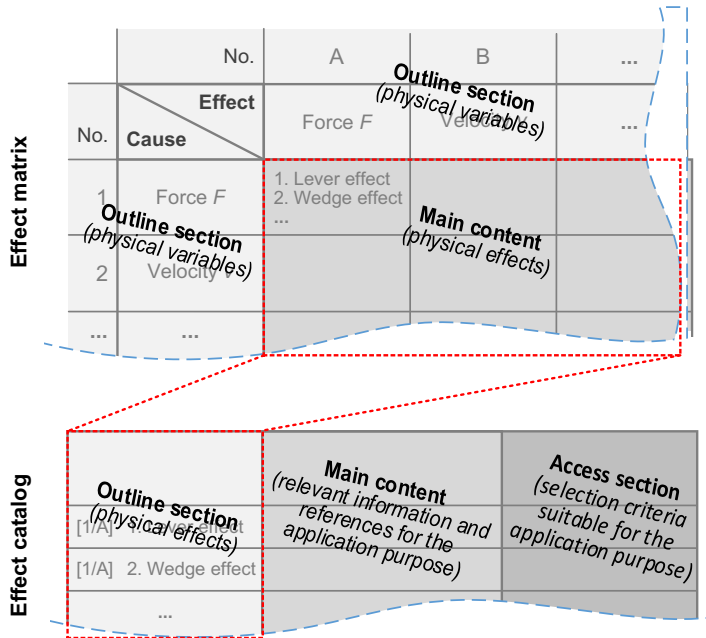
Figure 16. Interface between effect matrix and effect catalog as well as schematic structure of the effect catalog [translated from Vorwerk-Handing 2021].
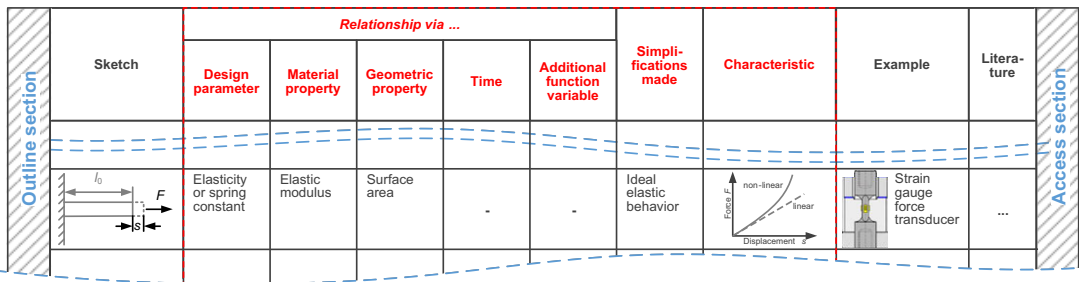
Figure 17. Structure of the main content of the effect catalog using the example of elastic elongation [translated from Vorwerk-Handing 2021].

possible for the user to quickly and intuitively grasp the type of relationship or possible characteristics of the relationship.

The essential *extension* compared to the main contents of existing effect catalogs lies in the differentiated consideration of the quantities that establish the relationship between the considered cause and effect. According to sections 3.1 and 4.1, the relationship between a causal function variable and the resulting effect is established by design parameters and/or a temporal relationship. Design parameters are composed of material and/or geometric properties of the component under consideration. The listing of both, superordinate design parameters and material and geometric properties, is consistent with the effect matrix (cf. Section 4.1) and is justified by the degree of abstraction selected by the user. In addition, other function variables can (passively) be involved in the cause–effect

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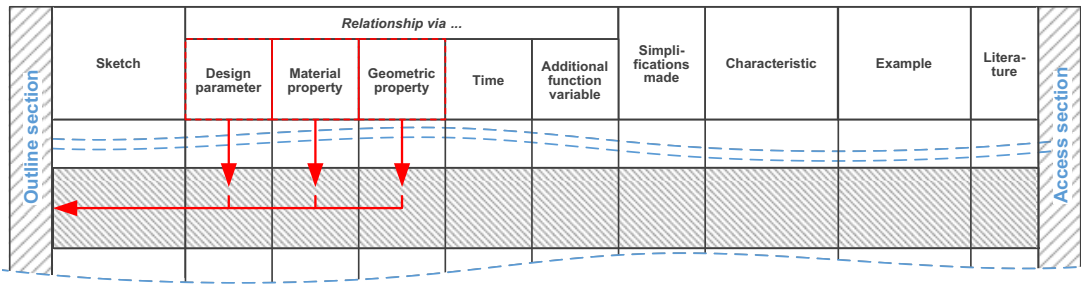
Figure 18. Structuring of the effect catalog via design parameters (material and geometric properties) [translated from Vorwerk-Handing 2021].

relationship. An example therefore is the Lorentz force, cf. equation 5 [cf. Wellstead 1979]:

$$\vec{F} = Q\vec{v} \times \vec{B}. \tag{5}$$

Equation 5 describes the force $\vec{F}$ which acts on an electric charge Q moving in a magnetic field (magnetic flux density $\vec{B}$) at the speed $\vec{v}$. According to the exemplarily illustrated relationship, both the speed $\vec{v}$ and the magnetic flux density $\vec{B}$ can be regarded as the cause of the resulting Lorentz force $\vec{F}$, depending on the point of view. Depending on the definition of the considered cause–effect relationship in the effect matrix, the further function variable involved in the physical relationship is listed in the main content of the effect catalog. The described extensions are summarized in the column "*relationship via …*" in Figure 17.

The presented extension of the effect catalog is useful and necessary for the intended purpose for two reasons:

- Through the differentiated listing of the variables that establish the relationship between cause and effect, it becomes obvious which dependencies exist and which variables must be known to be able to establish a metrologically usable, unambiguous relationship between cause and effect.
- Functionally relevant design parameters are of particular interest in the field of condition monitoring, but cannot be used as input variables in the effect matrix according to Section 4.1. In contrast to function variables, design parameters are not changed or converted. They establish the relationship between function variables and thus influence the relationship between cause and effect.

By determining the cause and effect of a physical effect, the (changed) relationship and thus the (temporal) change of the involved design parameters can be inferred. Consequently, all physical relationships in which the sought-after design parameter occurs are of interest, as potentially influenced relationships between function variables can be identified in this way. Proceeding from an initial relationship between the sought-after design parameter and an effect in the form of a function variable, effect chains can be built using the effect matrix from Section 4.1.

To be able to establish a relationship between a design parameter to be determined and potential measurands using the effect matrix, an intermediate step is necessary. In this intermediate step, the presented *extension of the effect catalog* is used. Filtering the effect catalog according to the design parameter to be

Required properties of a technical system according to effect-specific requirements and boundary conditions

Properties of a technical system according to Pahl, Beitz (2007)

Component-dependent properties

[Geometric properties]   *Material* properties

System-dependent properties

Kinematic properties

1.) General material properties

Property:	*Specification:*
State of aggregation	**solid liquid gaseous**

2.) Application-specific material properties:

Property(s): **Effect catalog – Category „Relationship via…" – Column „Material property"**	*Specifications:* **Check individually whether the respective property is available in a usable form**

Relationship via..

Design parameter	**Material property**	Geometric propterty	Time	Additional functional variables

1.) General kinematic properties :

Property:	*Specification:* **quiescent translatory rotatory**
Type of movement	

Property:	*Specification:* **uniform non-uniform oscillating**
Form of movement	

2.) Application-specific boundary conditions:

Property(s): **Effect catalog – Category „Relationship via…" – Column „Additional functional variables"**	*Specifications:* **Check individually whether the corresponding function variable is available in a usable form**

Relationship via..

Design parameter	Material property	Geomatric property	Time	**Additional function variables**

Figure 19. Structuring of the required properties of a technical system in the access section resulting from effect-specific requirements and boundary conditions [translated from Vorwerk-Handing 2021].

determined in the category "*relationship via …*" leads to function variables or physical effects, which are in principle usable for its determination. These functional variables or physical effects can then be used again as input variables in the effect matrix. This procedure is illustrated in Figure 18.

4.2.2.   Access section of the effect catalog

The aim of the access section of the effect catalog is to enable a preselection of potentially usable physical effects by the user. To enable a comparison between requirements and boundary conditions of the respective physical effects and the considered technical system, *required properties of the technical system* are derived from the effect-specific requirements and boundary conditions. This step is based on the statement from Pahl *et al.* (2007) that the *necessary conditions of a technical system for the realization of a physical effect can be described via geometric, material*

and kinematic properties of the technical system. In order to be able to carry out the desired comparison systematically and automatically, generally valid properties are defined. The starting point for this is the differentiation between *geometric, material and kinematic properties* of a technical system.

Geometric properties can be categorized in a generally valid way, e.g., according to Pahl *et al.* (2007) into the characteristics *type, shape, position, size* and *number* as well as correspondingly associated characteristics. However, since physical effects usually do not depend on a defined geometry, it is not possible to define required geometric properties for physical effects using such an approach. Since every material object has geometric properties, but a description of these cannot be brought into a generally valid relationship with the requirements of physical effects, geometric properties will not be further included in the effect catalog. However, information about geometric properties of the technical system offers potentials, which can be used in addition to the presented approaches. Particularly against the background of primary function fulfilment by function-relevant design parameters as well as installation space restrictions, the geometric properties of the initial system must be considered individually.

In order to enable a systematic preselection of potentially usable physical effects, material and kinematic properties are considered. On the one hand, *material properties* can be considered in isolation, related to the respective component of the technical system. *Kinematic properties*, on the other hand, always require a temporal and/or spatial reference and can thus only be considered at the system level [cf. Sena 1972]. Therefore, a differentiation of the required properties into *component-dependent* and *system-dependent properties* is made in the effect catalog (cf. Figure 19). It should be noted, however, that the distinction between component- and system-dependent properties depends on the particular point of view.

The *component-dependent properties* are considered in a first step as general material properties and in a second step as application-specific *material properties* of the respective component. The *state of aggregation* is used for a general differentiation, cf. Figure 19. Furthermore, the properties listed in the column "*relationship via …*" in the main content are adopted under the heading "*material property*". It must be assessed in each application whether or not the respective material property is available in a usable form.

As *system-dependent properties*, generally valid kinematic properties of the component in relation to the technical system, are considered in the first step

Required properties of a technical system			
Component-dependent *(material)* properties		System-dependent *(kinematic) properties*	
Property	Specification	Property	Specification

Figure 20. Structure of the effect catalogs' access section [translated from Vorwerk-Handing 2021].

[cf. Pahl *et al.* 2007]. According to Pahl *et al.* (2007), the *type and form* of the movement can be used for this purpose. Further specifications of the mentioned properties are *quiescent*, *translatory* or *rotatory* and *uniform*, *non-uniform* or *oscillating*, cf. Figure 19. In the second step, the function variables listed in the main content in the column "*relationship via …*" under the heading "*additional function variables*" are analyzed. In this analysis, it must be assessed in each application whether or not the respective function variable is available in a usable form.

In general, the information listed in the effect catalog in the columns "*simplifications made*" and "*characteristic*" can be used to preselect potentially usable physical effects.

The aim of the access section is to provide the opportunity to preselect physical effects based on a comparison between required properties of the component or system under consideration from the effect point of view and existing or *producible* properties, cf. Figure 20. It is explicitly pointed out that currently existing properties of a component can potentially be changed in order to allow for certain physical effects. In particular, material properties have this potential, provided that the function-relevant properties are not negatively influenced. This can be done by replacing or locally modifying the component in question. Since kinematic properties are usually directly functional-relevant, they typically do not offer this potential. An incompatibility between the properties of a technical system and required properties of a physical effect leads to the exclusion of the respective effect.

5. Assessment of the results

The results of Vorwerk-Handing (2021) were assessed in three consecutive steps using the main objectives from Section 3.2 and additional objectives described in Vorwerk-Handing (2021):

- Application of the developed catalog system using the development of a sensing machine element as an example [Vorwerk-Handing 2021].
- Logical verification by means of an argumentation and justification based on a comparison between the defined objectives and the achieved results [Vorwerk-Handing 2021].
- Initial validation by an exemplary application of the results in a cooperative industrial project [Harder *et al.* 2021].

With regard to the first two steps, it was found that the developed catalog system and its application enable a systematic establishment of a relationship between a specific state or process variable and potential measurands, taking the (existing) technical system into account. The overarching (positive) impact of the results is yet to be proven based on the situation described in the Section 1. However, Harder *et al.* (2021) provided an initial proof by applying the results of Vorwerk-Handing (2021) in the development process of a sensor-integrating plain bearing. In conclusion, Harder *et al.* (2021) state that "[…] a first application in the industrial project showed its[4] advantages. The systematic procedure, with which possible measurands are found for the desired variable of interest, reduces the likelihood of missing a relevant measuring principle. In addition, the approach is applicable

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[4]Annotation: Related to the application of the developed catalog system.

without previous experience about metrologically usable relationships or having an expertise with certain machine elements and supports therefore the development of unbiased solutions. [...] With these advantages, the presented approach is useful in the methodical development of sensing machine elements and thereby increases the effectiveness of the predictive maintenance of technical systems."

However, the initial validation also revealed that linking the generated effect chains with the (existing) technical system can be challenging. This is due to the fact that the effect chains typically contain a multitude of different physical effects. In order to be able to make a statement regarding the usability of an effect chain and the associated potential measurand, each of the included physical effects must be analyzed manually with regard to its occurrence in the (existing) technical system. To overcome this limitation, it is reasonable to model the system, its components and their multidomain interactions as well as their properties in a machine-readable way. Therefore, MBSE approaches could prove useful. One possible approach is to use information provided by a SysML model as suggested by Kraus *et al.* (2023). By doing so, effect chains can be filtered in an automated manner based on the already present – or through minor modifications introducible – geometric, material and kinematic properties of the system and its components. This would leave only effect chains and their associated potential measurands that are already present – or introducible – in the (existing) system. In this way, the identified limitation can be overcome and the usability of the approach can be ensured.

6. Conclusion and outlook

Obtaining reliable information about characteristic process and state variables in existing technical systems is key to their digitalization. However, it is oftentimes not obvious how these variables can be measured in the system, since a measurement can typically be realized in multiple ways – directly as well as indirectly. To solve this problem, the multipole-based effect catalog was developed by Vorwerk-Handing (2021). Starting from a process or state variable to be determined, the effect catalog and the associated approach allow for a systematic identification of potential measurands in existing technical systems by physical effects.

Starting from existing effect catalog systems as well as their limitations regarding a systematic identification of cause–effect relationships and the fundamentals of multipole-based modeling, a physically and logically justified structure of the multipole-based effect catalog was developed by Vorwerk-Handing (2021). Since structuring the catalog system strictly according to multipole-based modeling had weaknesses, the initially developed catalog system was pragmatically extended. Furthermore, a consistent differentiation between function variables and function-relevant design parameters was included by Vorwerk-Handing (2021). The inclusion of design parameters for the consideration of an existing technical system was developed based on multipole-based modeling. Due to its physically and logically justified structuring and the made pragmatic extensions, the developed catalog system is able to map every existing physical effect. This poses a major difference to the software prototype of Helms *et al.* (2013), which could only map 60% of the physical effects included in Koller (1998) and 80.5% of the ones included in Roth (2000).

In summary, a foundation has been created by Vorwerk-Handing (2021) to systematically include the transformations and changes of a process or state variable in a technical system in the identification process of potential measurands. The results of Harder *et al.* (2021) firstly demonstrated the potential of the effect catalog in the considered context. However, since the generation of effect chains using the analog multipole-based effect catalog is quite inefficient and prone to error, it was reasonable to digitalize the multipole-based effect catalog. This was carried out by Kraus *et al.* (2022, 2023), who developed an effect graph based on the multipole-based effect catalog by Vorwerk-Handing (2021). The effect graph allows for an automated generation of effect chains between a process or state variable to be determined and potential measurands. In addition, Kraus *et al.* (2023) extended the approach by Vorwerk-Handing (2021) by an automated robustness evaluation of the generated effect chains.

Future research is planned, in the context of an automated filtering of generated effect chains, linking a process or state variable to be determined and potential measurands, regarding their occurrence in the (existing) technical system. Therefore, a MBSE-based approach is pursued. Modeling the technical system, its components and their multidomain interactions as well as their properties in SysML, automated filtering of effects that do not occur in the technical system can be enabled. This allows the user to focus on promising effect chains for the realization of a sought-after measuring function.

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