Utilizing a graph data structure to model physical effects and dependencies between different physical variables for the systematic identification of sensory effects in design elements

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Abstract

Gaining accurate data from technical systems has become of interest, particularly in the context of condition monitoring and predictive maintenance. Hereby it is important to gather precise and reliable data. To accomplish this task, various sensors with different physical effects are used. Depending on the sensor's position and measurand, different models are necessary to describe the path from the desired variable of interest to the actual measured one. To support designers, a physical effect catalog was digitalized using a graph data structure, which uses the inherent properties of a graph to represent physical variables, physical effects and their relationships. This graph structure together with its applicability in a sensor selection process will be shown in this paper.

Keywords

Sensory function, synthesis method, effect catalog, support tool, SuDE

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1. Introduction and motivation

Resulting from the advancing digitalization in engineering, an increasing demand regarding precise and high quality data for condition monitoring and predictive maintenance of technical systems arises [1]. However, in this context, the systematic identification of suitable sensory effects as well as their integration into the system based on the pursued measurement goal and its subsequent target variable are oftentimes challenging.

In order to support developers in this process, Vorwerk-Handing [2, 3] proposed a new concept for an effect catalog, which is based on the principles of multi-pole based modeling. However, in order to be able to efficiently apply this catalog in the development and integration process of sensory functions, it must be made more accessible and thus usable. Consequently, in this contribution, a support tool is presented that is based on the effect catalog by Vorwerk-Handing and automated provides sensory effects for an application-specific measurement goal. The application of such a tool provides the potential to identify new and innovative sensor solutions within existing systems without integrating additional sensors.

2. Fundamentals

In this section the fundamentals for the developed support tool are introduced. First, the basics of multi-pole based modeling are described. Subsequently, the use and limitations of existing effect catalogs are explained. The focus here is on the effect catalog by Vorwerk-Handing [2, 3], which is based on multi-pole based modeling and forms the basis for the developed support tool. Furthermore, graphs are briefly introduced, which are used for the digital support tool. Finally, sensory utilized design elements and their methodical development framework are introduced as an application example for the developed tool.

2.1. Multi-Pole Based Modeling

Multi-pole based modeling is used to create abstract cross-domain models of technical systems based on elementary principles of energy conservation [4]. The idea behind multi-pole based modeling strategy is that different fields of physics, such as mechanics, electromagnetics or thermodynamics can be modeled in similar fashion. The modeling strategy uses analogies similar to the analogies proposed by Trent [5].

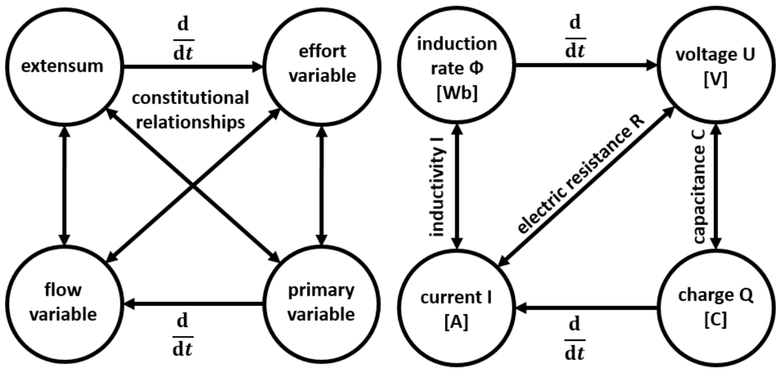

Figure 1: Multi-pole based model with the four defining variables and their relationships (left) and model of the physical domain “electricity” (right), both based on [2, 3]

The base distinction is made by so-called power conjugate variable couples, which can be found in the different sub-domains of the fields of physics. Each couple represents a power when multiplied. The power conjugate couple consists of two variables: the effort variable and the flow variable. To further represent a certain sub-domain (e.g. translational mechanics) a primary variable and an extensum are defined. The effort variable is hereby the time derivative of the extensum, and the flow variable is the time derivative of the primary variable. The resulting relationships can be seen in Figure 1 on the left. The different variables are also connected by so-called constitutional relationships, which are usually based on a functional parameter such as the capacitance or inductivity. An example for the physical domain “electricity” can be seen in Figure 1 on the right. [2, 4]

2.2. Effect catalogs

Effect catalogs serve engineers as repositories for existing knowledge and information regarding physical effects, which form the basis for the realization of (sensory) functions in technical systems [6]. There are different effect catalogs existing, like e.g. the one by Roth [7] or the effects database of Oxford Creativity Ltd. [8]. These catalogs mainly differ – besides their form of representation, analog or digital – in terms of their structuring based on the included variables as well as their extend of completeness in terms of included physical effects [2, 3]. Since these catalogs were originally developed for the identification of working principles for functions and thus establish a relationship between a desired effect and potential causes, they are not directly applicable for the systematic identification of sensory effects, in which measurable effects for an initial cause are sought [2]. In order to overcome this problem, Vorwerk-Handing [2] proposed a concept for a new effect catalog – the multi-pole based effect catalog –, which is based on the above presented multi-pole based modeling.

The multi-pole based effect catalog builds upon the different (sub-)domains of physics and utilizes them as base division. By systematically listing the different (sub-)domain specific variables from multi-pole based modeling – the flow variable, effort variable, extensum and primary variable – as input variables (rows) and output variables (columns) in the structure section, a two-dimensional matrix results. This matrix is referred to as effect matrix and maps existing physical effects between the different input and output variables in the structure section. Inside the effect matrix, the effect catalog itself is located. The effect catalog contains information about the different physical effects, such as their corresponding equations, influencing parameters as well as additional information, e.g. simplifications or assumptions and examples. [2, 3]

2.3. Graphs

Graphs are a type of data structure that aim to distinguish information into two main data types: so-called nodes and edges, also referred to as vertices and relationships. Nodes can represent data points and information, while edges represent a connection in between nodes. In this context, each edge connects exactly one node with another. Edges can be directional and non-directional. It is also possible to define different types of nodes and edges within one graph, which allows for a more detailed representation of the data and an easier search or querying. Graphs are therefore useful if many data points within a data set are linked with each other. A common application for a graph data structure is the representation of road networks, where a node represents an intersection or road end and an edge represents a road [9]. [10]

2.4. Sensory utilizable Design Elements

The idea of using the inherent physical properties of a not necessarily standardized design element within a sensory function is based on a similar approach by Vorwerk-Handing et al. [11] and was first introduced by Kraus et al. [12] in the context of the measurement of the opening degree of an industry valve. Those two ideas were taken up by Harder et al. [13] and restructured into the Sensing Design Elements classification, of which the Sensory utilizable Design Elements (SuDE) are of special interest for this work.

SuDE include all standardized as well as non-standardized design elements which show a certain physical characteristic, which can be exploited for a sensory function, e.g. the relative movement of a valve closing body versus the valve housing [12]. The main benefit of this approach is, that no additional components need to be integrated into the usually limited building space, while the measurement can be carried out at or very close to the actual point of interest. To support designers, Kraus et al. [14] introduced a method to identify and methodically select design elements from a technical system that show promising physical characteristics to fulfill a measurement task. The method gives an algorithmic structure to identify, select and score potential SuDE from a given structure of a physical system under the premise of knowing the desired target variable. The authors state several improvements that would lead to a higher acceptance of the method. Several of them can be tackled by developing a digital support tool, such as the necessity of an open-source effect catalog, less familiarity with multi-pole based modeling and the inclusion of an automated robustness check. The two main improvement points are highlighted in the structure of the method shown in Figure 3.

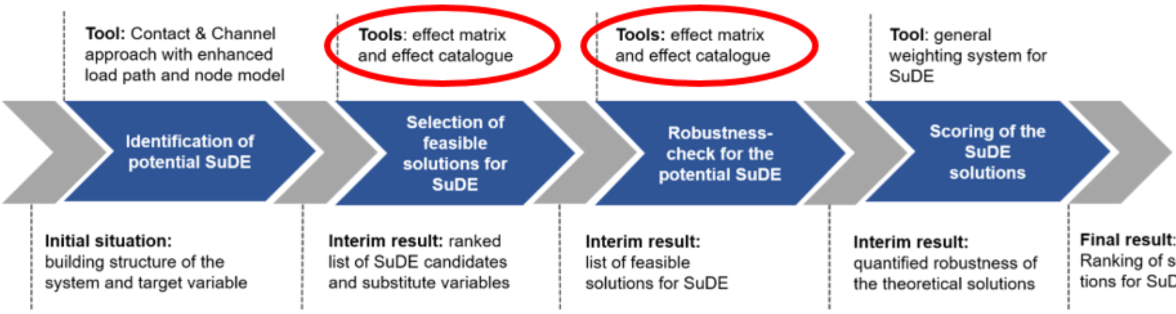

Figure 3: SuDE-identification method by Kraus et al. [14] with highlighted utilization of effect catalogs

3. Research problem and research goals

Gericke et al. [15] as well as Beckmann [16] state that methods developed within the science community often do not transfer well into practice. This can have many different reasons, e.g. because the entry hurdle for the user is too high, the method lacks intuitivity, specific knowledge and training is required or the method is not efficient enough due to a lack of automation [15, 16].

Effect catalogs serve as repositories for existing knowledge and information regarding physical effects as well as design-related data and therefore aim to support engineers in the identification of effects to realize a desired function [6]. However, since the majority of existing effect catalogs is still in an analog format, their application in practice is still low. This is due to the limited accessibility of the stored knowledge and information as well as their inefficient and ponderous manual operation.

In the context of the identification of usable sensory effects, potential measurands can be derived using analog effect catalogs. The query works by starting from the target variable to be determined and searching for existing physical effects that link the target variable to another, measurable physical variable. However, many sensory functions and sensors are typically not based on a single physical effect but on a linking of multiple effects [2, 3]. When using analog effect catalogs, the connection of physical effects is time-consuming and inefficient, since these linkages must be determined and connected by hand. Hence, in order to overcome this problem, the basis for the automation of this procedure is developed in this contribution by means of a support tool. The tool provides the possibility of automatically requesting effects and building effect chains to fulfill a desired sensory function.

Hence, the research question for this contribution is: How can a support tool be designed to improve the usability of the multi-pole based effect catalog by Vorwerk-Handing [2, 3] in the context of the identification of sensory effects and which data structure is suitable for this?

4. Effect graph – structure, development and application

To develop the data structure and the support tool, first a requirements assessment was done, by merging the requirements for a design catalog such as Roth [7], a digital support tool and the principle extensibility of the query algorithms. A digital support tool which accesses the chosen database is programmed and implemented into a GUI. The tool was then used together with the SuDE-Method on an example clutch. The results where then evaluated by comparing the solutions found and the usability of the tool compared to other knowledge repositories.

4.1. Analysis of the multi-pole based effect catalog

As already mentioned, the effect catalog by Vorwerk-Handing [2, 3] divides physical variables into effect causes and effect impacts. Effects can be searched for via the structure section of the effect matrix. If the searched cause-impact pairing does not exist directly, effects must be searched for by hand in order to indirectly link the state variables via several physical effects. This is tedious as many effect chains can typically be identified to fulfill the same sensory function and therefore must be evaluated and assessed regarding their usability.

On the effect side of the catalog, function-relevant parameters are listed and assigned to their respective physical domain. Based on the division into domains, the state variables can easily be assigned. In this case, this can lead to multiple entries in the effect side, since parameters can be used across domains. The strict separation of cause and impact allows to take into account the directionality of dissipative effects.

The further examination of existing effect catalogs, such as the one by Roth [7] or the effects database by Oxfort Creativity Ltd. [8], shows that these only contain a number of effects in the three-digit range. However, it is noticeable that the effects are composed differently. Effects link a varying number of state variables and parameters. As a result, effects and their associated variables can hardly be described in a uniform way.

4.2. Selection of database structure and modeling of the data

The challenge when selecting a database structure for the effect graph is it to find a suitable way to represent the information. In this context, the goal is to display the different physical effects as well as their influencing variables and parameters in the database. Due to the table structure of analog effect catalogs, a relational storage seems obvious, however the support tool needs to interconnect multiple physical effects from within the table, and the data is highly interconnected, which makes a graph data structure more suitable.

Furthermore, the amount of data contained by the effect catalog is small enough that the difference in performance between a relational database management system (DBMS) and a graph DBMS systems is negligible. When considering and modeling effect data using tables, it is found that they do not provide a suitable way to display the data. Correlations between variables represented by effects are complex, highly interconnected and irregular. It is difficult to make generalized analogies and to describe effects in a uniform way. Tables must be provided in advance with sufficient columns to represent the different number of variables and parameters. Nevertheless, effects with simple equations would leave attribute columns empty. In this context, graphs offer great flexibility to map the different effects in a suitable way. In addition, a graph is more flexible in the development compared to a table, since it can, e.g., better react to a change in models during the modeling process. Therefore, the graph DBMS neo4j is chosen. The flexibility of the structure further favors the constant adaptation of the DBMS to the user interface during its development.

The effect matrix by Vorwerk-Handing [2, 3] forms the basic systematic of the graph structure. Similar to the structure section of the effect matrix, domains and subdomains structure the physical variables. Based on this, the preliminary schema of the graph consists of three different layers: state variables, design parameters and effects, as well their MPBM substructure, cf. Figure 4. Effects bring functional variables into context [6] . In the case of effects, a distinction is made between varying functional variables and rigid design parameters.

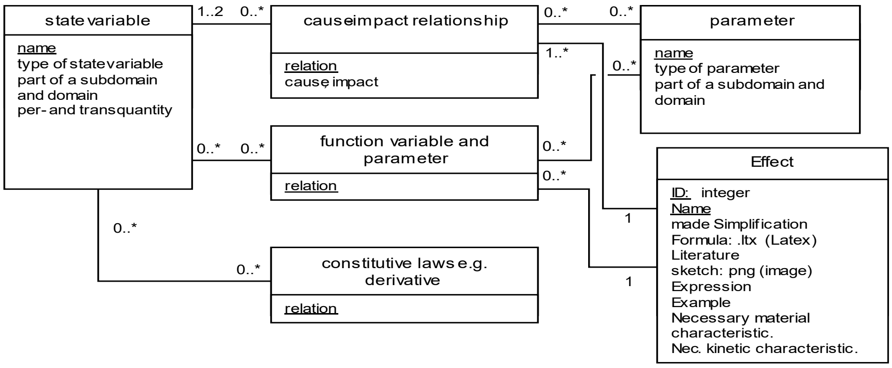

Figure 4: UML-modelling of the class types in the database and their relations

Each layer has a distinct type of nodes, divided into a substructure. The overall hierarchic structure resembels the effect matrix, so each node has a distinct position in the hierarchy. There are three distinctive substructures with nodes, which are linked via two main relationships. State variables, as start and end points of a query, are linked to effects via “CAUSE_IMPACTS”-edge relations, while additional relevant parameters are linked to the corresponding effects with “HAS_PARAMETER”-edges. The resulting structure, as well as the relationship between effects and state variables are illustrated in Figure 4 using the Unified Modeling Language (UML), which is a standardized representation method for modeling data and processes [17]. Data from the effect catalog should be represented in a UML class diagram as a basis for decision-making between a relational and a graph database. The information recorded in the requirements is to be represented in this diagram. Figure 4 illustrates the relationship between effects and state variables in UML.

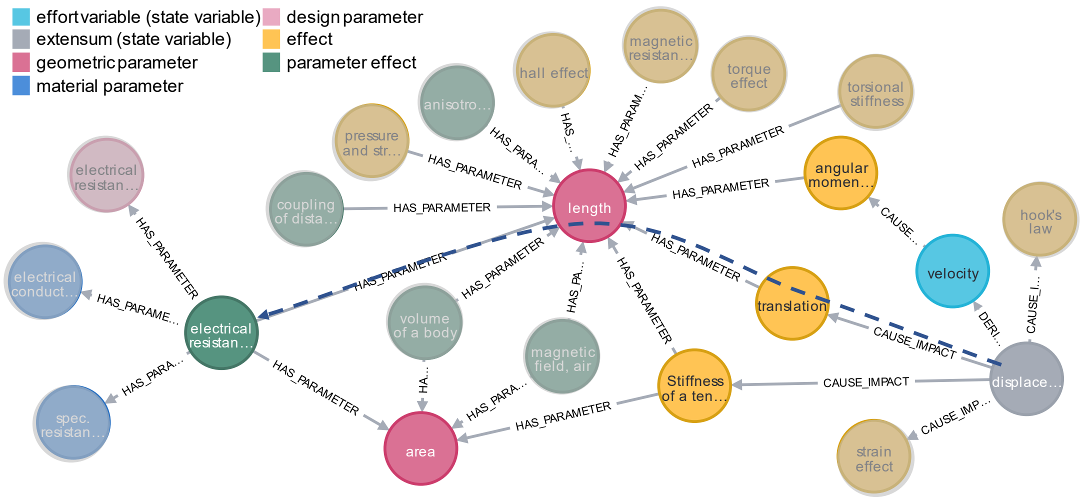

Figure 5: Example of found effect chains connecting the displacement s and the change in electrical resistance ΔR, within a simplified effect diagram and associated variables and effects (grayed out)

In total, the graph structure utilizes three types of relationships to connect the given node types. Each relationship type serves a particular purpose, and may or may not be included while querying the database. To query effects in the database, starting from the input variable, nodes connected by edges are visited to get to the desired target variable. In this way, a chain of related effects is formed. These related variables are referred to as an effect chain. In order to reduce the amount of query results, a filter is implemented in order to limit the query exclusively to state variables. Figure 5 shows an exemplary query, where two different effect chains between the displacement s and the change in electric resistance ΔR are shown. In addition, the different effects and variables are weighted. The weighting encourages the connection of effects via variables instead of switching to parameters. This helps to exclude compensation correlations.

4.3. User interface

Based on the selected database structure and the query to request the data, the python based user interface of the effect graph is presented in this section. It provides a simple way for the user to get suggestions regarding usable effects, effect chains, respectively, to fulfill the sensory function sought for. The query results are displayed in a list view and in a visual view, as shown in Figure 6.

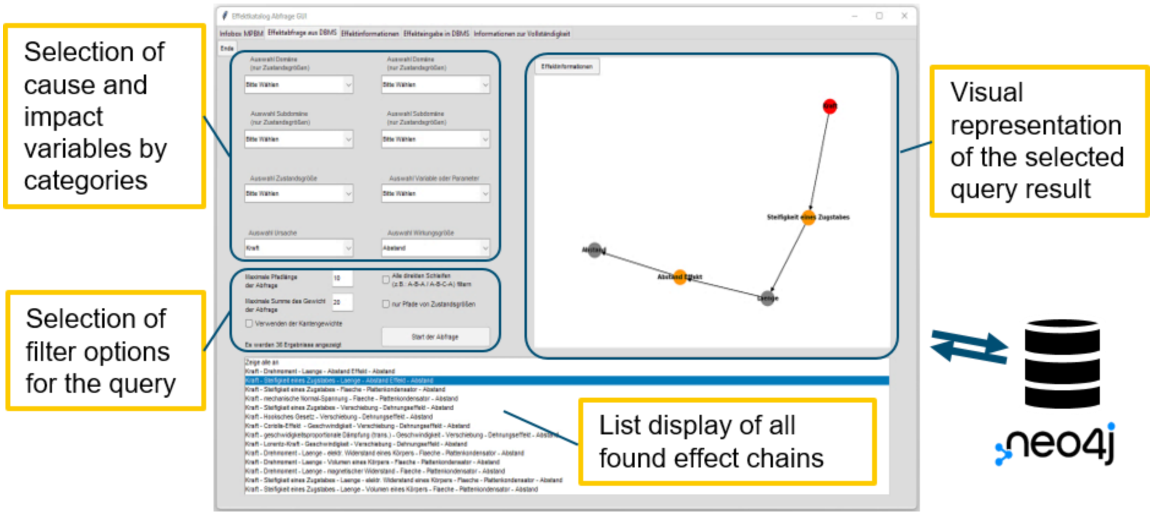

Figure 6: Graphical user interface of the support tool, shown is the query tab which allows the user to send queries to the DBMS neo4j

Further information about the effects can be retrieved in the next step. This includes information regarding, e.g. made assumptions. Constraints denote necessary properties of the system, which are required for the occurrence of an effect. An example therefore is a material dependency [18]. Likewise, if the effect can quantitatively be described by an equation, this equation is shown. Otherwise, proportionalities are given. Further properties are simplifications and restrictions. Here, the characteristic is to represent the functional connection of state variables occurring in the effect e.g., linear or non-linear connections within an effect. An equation in which variables have a linear correlation and others do not, is described as not linear. According to Löpelt et al. [18], transmission characteristics or measurement ranges are relevant requirements for sensors. The selection of effects according their magnitude is therefore important and the characteristic value ranges are suplemented, e.g., wether occurring stresses are in the MPa or kPa range.

4.4. Analysis, verification and application example

Structuring the graph in this way allows queries from cause to impact quantities. The modeling of effects and variable in this schema allows an easy permutation of effects. The graph database replaces the manual permutations for every variable of an effect, compared to a regular effects catalog or relation tables. The effects database is currently in build-up and expanded with effects continuously. The variables and parameter used in the multi-pole based effect catalog by Vorwerk-Handing [2, 3] are already implemented.

The evaluation is done by using the example of a single-plate dry clutch. Dry clutches enable a switchable transmission of torques. To have information on the clutch position or the distance between the clutch disc and the friction plate is necessary to implement additional functions for vehicles. For example, a start-stop function or hill-start assist requires the clutch position. To determine the position of the clutch, there are currently master cylinders equipped with displacement sensors. [19, 20]

The taks is to find sensor positions that determine the clutch position or clutch wear. The clutch position of the friction linings in relation to the pressure plate is the "point of interest" (PoI). The components of the clutch are checked for sensory usability. For this purpose, the steps according to Kraus et al. [14] are followed and possible alternatives to the measurement of the clutch position are sought. The central component of the PoI according to [14] is the friction lining. The change in the distance between the linings is to be determined. For this purpose, either the displacement s or the distance d between the linings need to be measured.

The potential SuDE are then checked for sensory usability. For this purpose, effects for displacement measurement or effects with an influence on the distance are identified by using the support tool. For this purpose, the program queries the search from the displacement to arbitrary variables with a maximum path length of four edges, to keep the solution space in a manageable size.

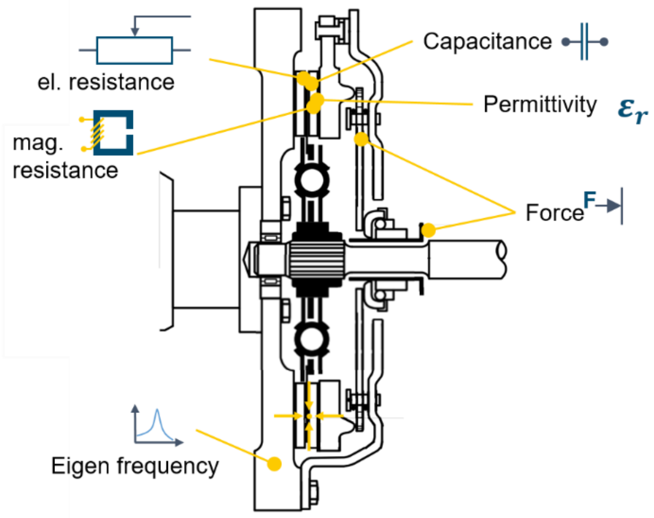

Figure 7: Identified measurement possibilities for a SuDE concept within a clutch, based on the clutch of Schaeffler Automotive Aftermarket GmbH & Co. KG [19]

The effects, which have no usable variables known to the user are sorted out. For example, effect chains that use a velocity are not tested further. Other chains contain effects that have limitations or are complicated to implement into the system. As an example, the Lorentz force is to be mentioned, which requires a moving electric charge, but has no direct relation to distance or displacement. Some of the remaining chains do not have a direct measurand as final node but represent nevertheless chains, which are regarded as in principle usable by the authors. Figure 7 shows effects or variables that can be used in this case. However, their practical usability has still to be evaluated.

Finally, the given results are be compared with the proposed effects by the effects database by Oxford Creativity Ltd. [8]. The database does not include variables such as displacement or distance in its request to measure parameters. Therefore, it was limited to indirect measurements of volume (29 results) and position (57 results). Users get in their query only the effect name, a reference to the corresponding Wikipedia page and a short generalized description. A comparison shows that the effects database of Oxford Creativity Ltd. [8] is more suitable for probing than for a concept selection.

5. Discussion and outlook

Integrating sensory functions into technical systems in order to provide accurate and high quality data for condition monitoring and predictive maintainance is oftentimes challenging for engineers. Hence, the aim of this contribution was to develop a digital support tool, which is based on the multi-pole based effect catalog by Vorwerk-Handing [2, 3] and automatically suggests potentially usable sensory effects, effect chains, respectively, and thus supports engineers within this process. This not only increases the efficiency of the identification process compared to analog effect catalogs due to automation but also minimizes the entry hurdle for the user, since no specific knowledge is required to operate the support tool.

In order to develop the support tool, in the beginning, the content and structure of the multi-pole based effect catalog by Vorwerk-Handing [2, 3] was analyzed and requirements arising from the method to identify SuDE within a system were derived. The results of chapter 4 show that it is possible to model physical variables and their relations based on multi-pole based modeling inside a graph data structure. The graph has the inherent advantage, compared to the common table style structure of the original multi-pole based effect catalog by Vorwerk-Handing [2, 3], that relations between the variables are directly represented inside the database. Those direct connections allow the user to gain effect chains by using relatively simple search algorithms, which are already defined for graphs as a data structure. The utilization of the node and edge classes allow a diversified representation of each variable, effect and relation. This decreases search time within the data structure since certain node or edge types can be excluded during an iquiry. It also allows an easy implementation of more physical effects because only a node and its respective connections need to be added to represent a new physical effect inside the graph. For an easy access to the data and to generate the effect chains, a graphic user interface was developed, which automatically queries the desired chains from the database, based on the user's inputs. To show the applicability, the method to identify SuDE was applied to a clutch and the effect graph was used instead of the analog effect catalog. The ability to quickly generate effect chains turned out to be useful, especially in comparison with other effect catalogs. The effect information and disturbance detection facilitate the concept development. This highly decreses the effort for the user to generate effect chains compared to the analog effect catalog and thus accelerates the method and makes it more accessible with less knowledge. It also opens up the possibility of analyzing the surrounding effects of the considered effect chain, as exemplary indicated by the greyed out effects in Figure 5. This helps to identify disturbances which might occur due to other physical effects, which are parallel to the intended one. In this context, one future target is to automatically identify and rate those disturbanes to get a better understanding of the uncertainties within a system. However, the developed support tool does not yet offer the possibility to systematically identify disturbance factor-induced effects that may influence a considered effect chain. Therefore, it is planned to extend the user interface and provide standardized disturbance factors, e.g. the ones defined by Welzbacher et al. [21]. Based on the disturbance factors selected by the user, unintended effects, effect chains, respectively, that may influence the considered effect chain can then systematically be identified.

While the base structure of the graph is promising for future use, several problems need to be addressed before the full usability of the support tool is reached. Firstly, more physical effects need to be added to the graph to fill it with more information. Secondly, multiple different search options should be pre-provided for the user to increase the usability of the tool, e.g. querying of derivation or parameter relations. In addition, the current query design needs to verified or replaced by more efficient or selective queries. Thirdly, an automated detection and rating of disturbances of the system should be implemented to identify their possible impacts. Finally, a modelling method should be developed, which allows the connection of the modeled system with the generated effect chains. If this is based on a SysML approach, for example, the manual effort required to apply the SuDE-method will be highly reduced.

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