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The C&C² Approach as a Thinking Tool in Mechatronic Systems

Felix Prager[a], Peter M. Tröster[a]*, Albert Albers[a]

[a]*Karlsruhe Institute for Technology (KIT), Kaiserstraße 12, 76131 Karlsruhe, Germany*

* Corresponding author. Tel.: +49-721-608-47252; fax: +49-721-608-46051. *E-mail address:* peter.troester@kit.edu

Abstract

In recent times, interest in cross-domain system modeling has seen a significant increase. Despite the proven success of the Contact and Channel Approach (C&C2-Approach) in mechanical system modeling, a procedure for cross-domain applications has been largely absent. In this research, we discuss how mechatronic systems can be modeled with the C&C2-Approach. Based on extensive literature research, which allowed us to identify cross-domain reference models, we are introducing the integration of bond graphs into the C&C2-Approach. The principles of bond graph theory make it possible to represent embodiment function relations (EFRs) in non-mechanical domains. For this purpose, only a few extensions to the key elements of the C&C2-Approach are required: On the one hand, the information about the predominant direction of the energy flow is integrated into the C&C2-Model, while, on the other hand, we add the information about whether the EFR is static or dynamic. These adaptations offer the further possibility of building a bridge to mathematical models. At this point, a bond graph can be derived from the C&C2-Model and used to analyze the systems' behavior in a simulation. This research therefore supports developers in modeling mechatronic systems and enables simulations at an early stage of product development.

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1. Introduction

The increasing electrification and digitalization of once purely mechanical products requires an adaptation of the methods used to design these systems. One method that is used in the iterative process of analysis and synthesis of the design process is the Contact and Channel Approach (C&C²-Approach) [1]. It is a tool used for visualizing embodiment function relations (EFRs). Although the definition of the C&C²-Approach allows a generalized usage, it has so far been applied almost exclusively to mechanical problems [2]. The still little-researched handling of non-mechanical domains therefore leads to uncertainties and ambiguities about the application, which prevents its use in these areas.

In the following, it will be discussed how the C&C²-Approach can be practically applied to mechatronic problems. This requires some extensions to the thinking tool, which will be presented by the cross-domain definition of the C&C²-Approach. The theoretical foundations are provided by the bond graph theory, which is known for its generalized usability [3]. In contrast to the purely graphically descriptive C&C²-Approach, the bond graph theory is a mathematical modeling method. Such mathematical models are often used in modern product development for behavior analysis [4]. To incorporate the option of simulation into the design process as early as possible, the generation of simulations from C&C²-Models represents an additional aim. This new capability is made possible by deriving a bond graph from a C&C²-Model. As a result, the model elements of the C&C²-Approach can be assigned a direct mathematical meaning, whose influence can be utilized in simulations.

2. Methodology and Research Questions

The universal definition of the C&C²-Approach offers the potential to open the thinking tool to a broader range of

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applications. In a review of the last twenty years of application experience, Grauberger et al. [2] call for a methodology to handle these domains. To identify the deficiencies of the C&C²-Approach in non-mechanical applications, we compared the thinking tool to reference models. Here, mainly (system) equation-based modeling methods were identified that allow generalized modeling (such as the block diagram of control engineering [5]). However, these methods usually do not represent the physical effects as such, but the resulting equations, which is why they are incompatible with the C&C²-Approach. The multipole-based modeling of bond graphs and Kirchhoff networks [6] finally provided a remedy. Since Kirchhoff networks are only interesting for users who are familiar with electrical circuits, the neutral bond graph theory was chosen as the reference model. After all, the C&C²-Approach should be made attractive for product developers from different disciplines.

This leads to the following research questions:

- RQ1: How can the C&C²-Approach be applied to mechatronic domains?
- RQ2: How can a mathematical model be derived from a C&C²-Model to make it suitable for a simulation?

3. State of the Art

Mechatronic products are developed using domain-specific models that are often only understood by the specific experts. Although science has realized from the concept of energy that all subdomains follow the same laws, for historical reasons, the domains are still considered separately [7].

Regarding mathematical models, which are primarily based on differential equations, the theory of bond graphs was published in 1959 [8]. It is a domain-independent modeling method that allows to create models in any domain while always using identical quantities [4].

3.1. Contact & Channel Approach (C&C²-Approach)

The C&C²-Approach is a graphically descriptive modeling method that supports developers in reducing problems to the essential EFRs [9]. It includes model elements where the key elements are particularly noteworthy (Fig. 1). They are the main components of every C&C²-Model and can represent any technical function [10]. The set of rules for using the model elements is defined by the three basic hypotheses of the C&C²-Approach, which are also mentioned in Fig. 1. The key elements are defined as follows:

- Working Surface Pair (WSP):

Working Surface Pairs are surface elements. They are formed when two arbitrarily shaped surfaces of solid bodies or generalized interfaces of liquids, gases, or fields get into contact and are involved in the exchange of energy, substance, and/or information [10].

- Channel and Support Structure (CSS):

Channel and Support Structures are volume elements. They define the volume of solid bodies, liquids, gases, or field-permeated spaces that connect exactly two Working Surface Pairs and allow the conduction of matter, energy, and/or information between them [10].

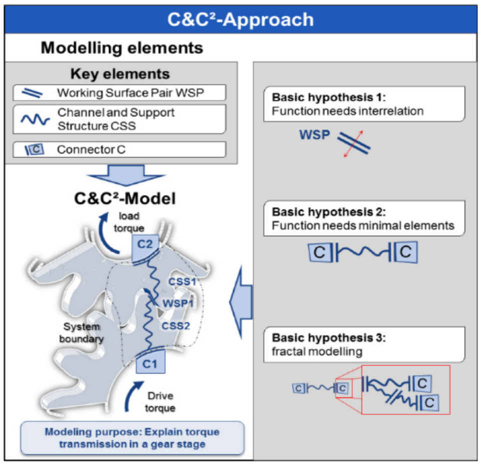

Fig. 1: Key model elements of the C&C²-Approach [11]

- Connector (C):

Connectors integrate the effects that influence the system and are located outside the design area, in the sub-system modelled with the C&C²-Approach. Connectors have a representative Working Surface (WS) and represent a parameterized model of the relevant system environment; thus, they are within the observation area, but not within the design area [9, 12].

For the subsequent synergy of the C&C²-Approach and the bond graph theory (Chapter 4), some aspects are further relevant. The C&C²-Approach is based on causality. The interface between cause and effect forms thereby the WSP [10]. It should also be noted that all bodies can store energy; in the C&C²-Approach, CSSs represent the energy-storing elements and can therefore have a reciprocal effect on other CSSs [10].

If the system boundaries of a technical system are defined far enough, the C&C²-Model creates a closed circle of interactions. In this context, it is ultimately possible to integrate the concept of state from physics into the definition of the C&C²-Approach [10]. The following work is intended to build on these *generalized* ideas of the C&C²-Approach to further expand the possible applications of the method.

3.2. Bond Graphs

The bond graph theory explains technical systems through universal principles such as the conservation of energy, *change* as a characteristic of all systems, and the ability to describe any system's behavior through the *correct interconnection of standard elements*. Although technical systems are usually divided into static and dynamic systems, they are strictly all dynamic. However, a static view simplifies the analysis of a system considerably, provided that the change in the system is negligible for the purpose of the investigation [4]. The variables driving the change (flow and effort variables) use their product to determine the power prevailing in the system and thus, the energy. The specific behavior of the system is determined by the type, number and interconnection of the standard elements [4, 8]. These principles, anchored in the

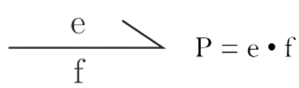

Fig. 2: Power bond, describing the power P and thus the energy in the system through the product of the effort variable e and the flow variable f [8]

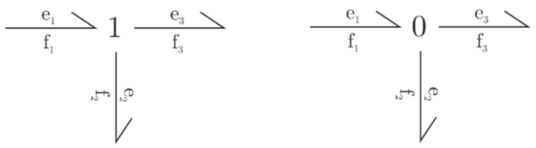

Fig. 3: Series connection (1-junction) and parallel connection (0-junction) in bond graph notation [8]

bond graph, provide an intuitive representation of cross-domain (including nonlinear) relationships and provide a mathematical model that can be used to study system behavior.

The flow of energy, meaning the power transfer between the system components, is represented in the bond graph via so-called power bonds by a directed half-arrow (Fig. 2). Along the power bond runs the power P, which results from the effort variable e and the flow variable f [8]. These generalized variables can be found in any domain.

The building blocks of a system, which are connected by the power bonds, are represented by so-called generalized standard elements. These are represented by R, I and C elements and behave identically regardless of the domain. For a tabular overview of the generalized standard elements in the respective domains, please refer to Schmitt and Andres [8].

To fully describe a system, two additional model elements are required. Firstly, the source from which the energy is fed into the system, and secondly, the converter (two-port element) that transduces energy, for example, to enable power transfer between the domains. In the case of the source, a distinction is made depending on whether the flow or effort variable is specified, and in the case of the converter, depending on the relationship between the input and output variables [3, 4].

How the model elements in the system are interconnected is shown via the so-called junctions in the bond graph. Depending on whether the standard elements are connected in series (1-junction) or in parallel (0-junction), there are two different types of junctions (Fig. 3). At a junction, either the effort or the flow variable of all power bonds connected to the junction is identical, while the corresponding other generalized variable at the participating power bonds adds up to zero [4].

After an introduction to the basics, the creation of causal bond graphs will be briefly discussed. A systematic approach must be followed when creating a bond graph. Please refer to the formal methods of Roddeck [4] in the electrical and mechanical domains. However, once the bond graph has been created, it is not yet a mathematical model; it must be causalized beforehand and can then be interpreted by a computer. Since today's simulation programs, such as 20-sim or Dymola automatically causalize when creating a bond graph, a more detailed explanation will be omitted.

3.3. Case Study Low-Pass Filter

The cross-domain definition of the C&C^2-Approach will be illustrated in Chapter 4 based on the case study of a low-pass filter. The example was chosen such that engineers should already be largely familiar with it and the focus can therefore be placed on the novel C&C^2-Model formation as well as on the bond graph that can be derived from it.

In the case study, a second-order low-pass filter is analyzed, which, unlike to the first-order low-pass filter, contains an additional inductance in series with the resistor (Fig. 4). This provides greater frequency suppression above the cutoff frequency and thus separates the desired frequency band better.

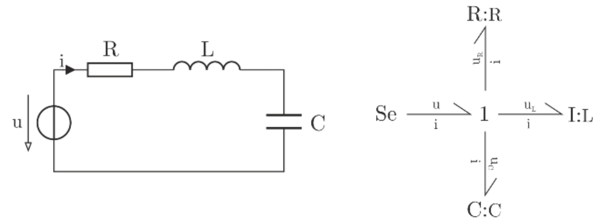

Fig. 4: Second-order low-pass filter with corresponding bond graph [8]

4. Results

To model mechatronic systems with the C&C^2-Approach and derive bond graphs from it, several steps are required. First, the modeling is done using the C&C^2-Approach. For mechatronic systems, adapted key elements are necessary. The model elements are then transferred to the bond graph and simplified step by step.

4.1. Thinking Tool for Mechatronic Systems

To be able to illustrate mechatronic processes using the C&C^2-Approach, the bond graph is taken as a reference. With the cross-domain definition of the C&C^2-Approach, it becomes possible, for example, to differentiate between a power transmission that serves to fulfill a function and a data transmission that merely specifies a function. For this purpose, the basic idea of bond graph theory, namely the energy flow, is integrated into the C&C^2-Approach. This requires two adjustments to the current key elements, which are illustrated below based on the case study from Matthiesen [12] (Fig. 5).

In contrast to the C&C^2-Model, the bond graph is a directed graph. The direction of the arrow on the power bond indicates the direction of energy flow (Fig. 2). Without additional information elements, such as a force vector, it is not yet possible to read from a C&C^2-Model in which direction the energy flow is propagating or from where the energy flow originates. Since actio = reactio always applies in technical systems, a C&C^2-Model is also valid without such a directional assignment. A more profound understanding of the system, however, requires knowledge of how the energy flow is directed through the system. To put it in a nutshell, in a C&C^2-Model, the CSSs represent the energy flow in a technical system. However, intuitively including the direction of flow by adding an arrow to each CSS (as in electrical engineering)

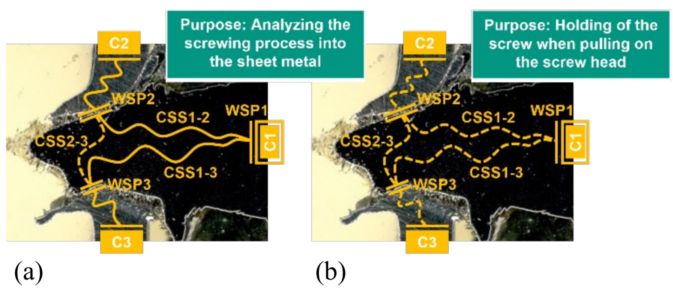

Fig. 5: Illustration of the cross-domain C&C^2-Approach using the example of a screw connection according to Matthiesen [13]

would make a C&C^2-Model unnecessarily confusing. Namely, the actual flow direction of some CSSs is not always determinable or significant. Due to the primary goal of a C&C^2-Model – to promote the understanding of the EFR [9] – an arbitrary definition of the energy flow directions (only for the sake of syntax) should be avoided at all costs. CSS2-3 serves as an example of such a CSS where the direction of flow cannot be clearly defined (Fig. 5). To illustrate the direction of energy flows in a C&C^2-Model, the so-called source Connector is introduced. It is proposed to represent it by a double-edged Connector (Table 1), which represents the source or origin of the energy flow. This enables the model observer to interpret the direction of the energy flows at the CSSs. Of course, several double-edged Connectors can occur in a C&C^2-Model. In the screw example (Fig. 5), the model element C1 is marked by such a source Connector. This indicates that the energy fed into the system originates from this model element. The example also shows that the energy supplied by the source element need not always be positive. In Fig. 5 (b), for example, a tensile force emanates from the source Connector C1. Consequently, a negative force acts on the system.

The second adaptation of the key elements lies in the way the CSS is represented. As already mentioned, in analogy to the bond graph, the CSS is intended to represent the energy flow. However, an energy flow only exists if effort and flow variables are present at the same time. If both generalized variables are different from zero, this is known as a dynamic system, and only in this case is it beneficial to create a bond graph. However, static systems are also analyzed using the C&C^2-Approach. To distinguish between CSSs with and without energy flow, the dynamic and static CSSs are introduced below (Table 1). As usual, if a CSS in the C&C^2-Model is a dynamic active connection, it is represented by a continuous curved line.

In Fig. 5 (a), almost all CSSs are characterized as such, since the effort variable (force) and the flow variable (movement) are present at the same time. Only one CSS (CSS2-3) is shown differently; the dashed curved line represents a static CSS. In the case of CSS2-3, the effort variable (force) exists, but no flow variable (movement), as the deformation of the screw tip is negligible. The second test case (Fig. 5 (b)), on the other hand, involves only CSSs. Since the screw remains anchored in the sheet metal, all flow variables (movements) are missing. The distinction between dynamic and static CSSs is therefore not only of great importance for graphically representing mechatronic system behavior, but also for identifying all dynamic CSSs for transferring the C&C^2-Model in a next step into a bond graph.

Table 1: Key elements in the cross-domain definition of the C&C^2-Approach

Working Surface Pair	Node (demarcation of system components)
Static Channel and Support Structure	No energy flow (static view)
Dynamic Channel and Support Structure	Energy flow (dynamic view)
Source Connector	Origin of the energy flow & System environment
Connector	System environment

4.2. Deriving a Bond Graph from a C&C^2-Model

Chapter 3.1 has already mentioned how the concept of state is anchored in the definition of the C&C^2-Approach. In this context, the CSS can be understood as a system component that can be represented by the R, I or C standard elements of the bond graph theory. The CSS can thus either store or dissipate energy. Thereby, the model of the bond graph automatically adapts to the selected abstraction level of the C&C^2-Model (the fractal character of the C&C^2-Approach is thus continued in the bond graph) – depending on how detailed a EFR is described via a CSS, the system component in the bond graph is correspondingly detailed. According to Table 1, only dynamic CSSs can be included in a bond graph, as only these have a non-zero energy flow.

The WSP, in turn, identifies the connection point between two or more CSSs. It can therefore be understood as a junction between system components, whereby the CSSs at this junction are either connected in series (same flow variable) or in parallel (same effort variable). The WSP thus connects the CSSs according to the same principle as a 1- or 0-junction connects the bond graph elements. When converting a C&C^2-Model into a bond graph, it must therefore be determined at all WSPs whether the connected CSSs share either the flow or effort variable. In addition to its function of forming the connection point between CSSs, in some situations, the WSP also has the function of converting generalized variables in the system. This allows different domains to be connected with each other, as well as describing the conversion of system parameters within a domain. The connection point or the connection surface at which the power is exchanged between system components thus represents the WSP and is specified in the bond graph notation via the converter element. As with the junctions, it is necessary to determine which of the two converter elements applies to the given test case. This depends on the ratio in which the generalized variables are converted to each other.

Just like the CSS and the WSP, the third key element of the C&C^2-Approach – the Connector or, more precisely, the source Connector – has a counterpart in bond graph theory. As the name suggests, the source element of bond graph theory represents the energy fed into the system. When transferring the source Connector to the bond graph, however, it is always necessary to determine which of the two possible source elements is represented. This can be determined by identifying which generalized variable (flow or effort variable) is specified by the source Connector. The *simple* Connector also has a meaning in the bond graph if it is involved in the dynamic EFR. In most cases, however, it is only relevant in the creation of a bond graph and can be eliminated at the end.

Finally, it is important to address a point mentioned in Chapter 2.2: A bond graph can only be created from a C&C^2-Model if the system boundaries are chosen appropriately. The

Table 2: Corresponding bond graph elements to the key elements of the C&C^2-Approach

C&C^2-Approach		Bond graph theory
Working Surface Pair	⟺	Junction or converter
Dynamic Channel and Support Structure	⟺	R, I or C standard element
Source Connector	⟺	Source element

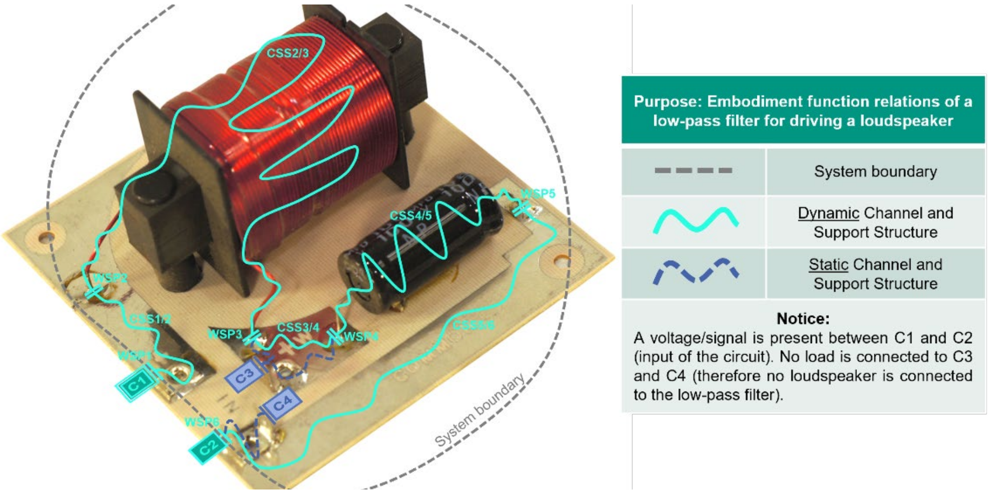

Fig. 6: Applying the cross-domain definition of the C&C^2-Approach to the case study of a second-order low-pass filter [14]

system boundaries must be selected in such a way that a closed loop is created. Only a “closed loop of cause and effect” [10] can provide all state variables to fully determine a mathematical model. If all shape or system parameters (such as the inertia mass of a shaft) are known for a case under investigation and its C&C^2-Model, a complete bond graph can be created.

4.3. Practical Example using a Low-Pass Filter

The predominantly theoretical explanations for the creation of a C&C^2-Model in the domains of mechatronics and its transfer to a bond graph will now be illustrated using the example of a low-pass filter. First, a closer look will be taken at the C&C^2-Model of the case study (Fig. 6). For a clearer representation, two different colors are used to distinguish between static and dynamic processes. Due to this categorization, it is evident that the (retroactive) influence of the downstream system elements is not included in the model consideration – the terminals of the positive and negative poles are open and therefore carry no current. Therefore, only one of the two generalized variables (the effort variable) is present at the terminals, which is why static CSSs emanate from these terminals in the C&C^2-Model. The low-pass filter is therefore analyzed unaffected by downstream components. Which influences are excluded when analyzing a system component depends entirely on the modeling purpose. Starting from C1 (source Connector), the signal is fed into the electrical circuit. The current is then conducted via the PCB to the coil (CSS1/2). Continuing from the coil, the current flows via the PCB to the capacitor (CSS3/4) and from there back to the negative input. The output signal, which is intended for the downstream system elements, can be tapped in parallel with the capacitor.

For the final transfer of the C&C^2-Model into the bond graph, the model is created using the formal methods for creating acausal bond graphs (electrical domain) from Roddeck [4]. Fig. 7 (a) shows the acausal bond graph after performing steps 1–3 of the formal method. The WSPs represent the locations of the potential (effort) differences and are therefore represented by 0-junctions. In addition, each CSS is embodied by one (or more) system component(s) and connected to the WSPs via 1-junctions. The selected direction of the power

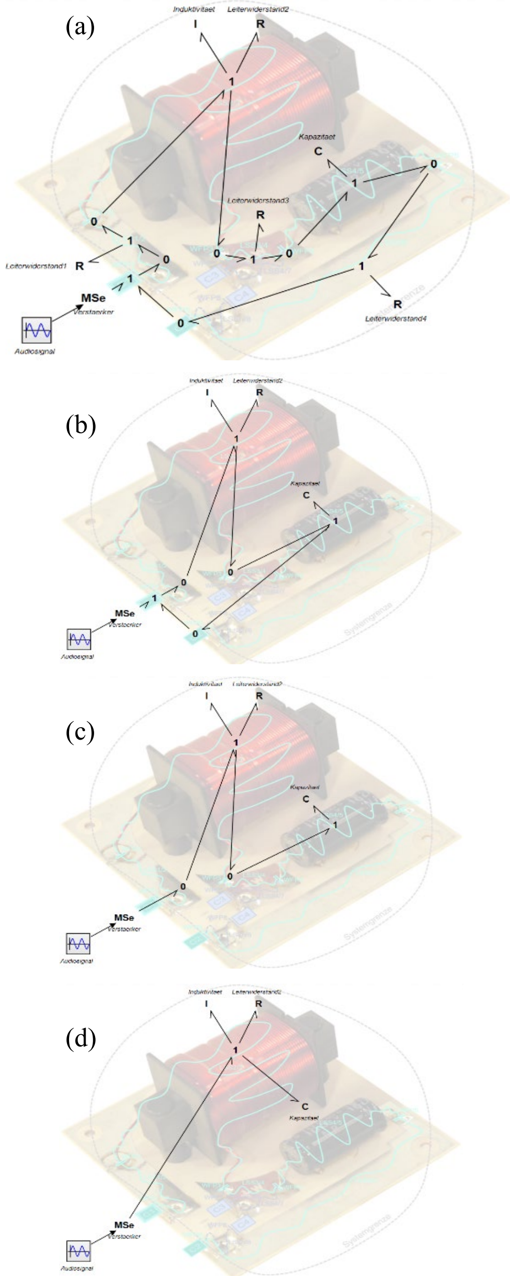

Fig. 7: Creation of a bond graph according to the formal methods [4]

bonds corresponds to the direction in which the signal is transmitted. In the following Fig. 7 (b), the ohmic resistances are eliminated from the bond graph, which are considered insignificant for the model consideration. The fourth step of the formal method is then shown in Fig. 7 (c). Here, the zero potential, which corresponds to the negative pole of the input and output (C2 & C4), was removed from the bond graph. The bond graph is now almost finalized. With the fifth step of the formal method, some superfluous junctions are removed from the bond graph according to the simplification rules [3] and the final bond graph for the C&C²-Model is obtained in Fig. 7 (d). Of course, the bond graph for the low-pass filter can also be created *intuitively*, as was done in Chapter 3.3 for the same electrical circuit (Fig. 4). However, the application of the formal method for creating acausal bond graphs is applied step by step to prepare the reader for the derivation of more complex bond graphs.

5. Discussion

The proposal to integrate the principles of bond graph theory into the C&C²-Approach created the basis for a generalized usability of the thinking tool, which can also be used to consider systems from other specialist areas (outside of mechatronics). At this point, the procedure was illustrated using a straightforward case study. The procedure proved to be intuitive and comprehensible. This finding was confirmed by further investigations, also outside the purely electrical engineering domain.

The cross-domain definition of the C&C²-Approach ensures an unchanged use of the model elements and thus supports intuitive application. For example, in the low-pass case study (Fig. 6), the CSSs interact with the WSPs in the usual way and transfer the energy flow in the process. In addition, the key elements have not been completely renewed, but merely assigned further properties. For example, the source Connector retains all the properties of the Connector and is additionally assigned the function of feeding energy into the system.

Another significant advantage of the cross-domain definition is the simplified step from the C&C²-Model to the simulation. For the first time, a mathematical interpretation can be assigned to the model elements, which enables the developer to derive a mathematical model directly from the created C&C²-Model. Simulatable design also makes it possible to create a more productive design process. The EFRs to be developed must now no longer be assessed *by eye* using the C&C²-Model, but the design parameters can be examined qualitatively using a simulation. After each iteration of analysis and synthesis [1], a bond graph can be derived from the C&C²-Model and used to analyze the design parameters that require optimization.

6. Outlook

The cross-domain definition of the C&C²-Approach offers considerable potential for the thinking tool. This contribution should lay the foundation for this use. However, there are still some remaining topics for research to reinforce the results:

- Utilization of further domains:

For the proposed cross-domain definition of the C&C²-Approach, a generalized usability is claimed. So far, this has been illustrated using mechatronic examples. To extend the results to other domains, it would be desirable to investigate hydraulic, thermal or optical systems, for example.

- Study to validate the results:

In general, the results presented here have yet to be established. A particularly informative study could address the question of to what extent the cross-domain model elements increase understanding of the EFR.

- Automated derivation of bond graphs from C&C²-Models:

With the help of a software in which C&C²-Models could be created and the relationships between the model elements are automatically stored, an automatic derivation of the bond graph or an export to a simulation program could be realized.

- Simulation of a C&C²-Model using the corresponding bond graph:

To underpin the benefits of the cross-domain definition of the C&C²-Approach, it would be beneficial to examine a real case study (with real design parameters or system parameters) – ideally in the context of the design process of a new product.

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