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Procedia CIRP 70 (2018) 475–480

www.elsevier.com/locate/procedia

28th CIRP Design Conference, May 2018, Nantes, France

From Reality to Simulation – Using the C&C²-Approach to Support the Modelling of a Dynamic System

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Abstract

Knowledge of a systems dynamic behavior is often necessary for successful product development. To gain this knowledge, simulation models can be used. In the process of building up these models, the real dynamic system is simplified. A challenge of simplification is the identification of relevant parameters of the technical system, so that the simplified simulation model can be used to gain necessary knowledge about the system behaviour. In this contribution it was investigated, how the C&C²-Approach can support the identification of relevant parameters for the simulation model. As method of examination a Single Case Study was used. In the case a simulation model of an overload clutch was developed by a design engineer who was already familiar with the C&C²-Approach. To gain qualitative findings a retrospective semi-structured interview was conducted with the design engineer. The result of this interview was that using the C&C²-Approach in the system analysis was evaluated as supportive by the design engineer in the process of simplification and documentation of the system. The simplification was supported through the structuring of the system using the key elements of the C&C²-Approach. The design engineer followed the flow of forces and focused on the embodiment that influences the torque transmission of the technical system. The results of the analysis with the C&C²-Approach were visualised and documented in a C& C²-Modell, which supported the collaborative working and discussing with other design engineers.

Peer-review under responsibility of the scientific committee of the 28th CIRP Design Conference 2018.

Keywords: Analysis; modelling; dynamic systems; C&C²-Approach; power tools

1. Introduction

In product development, simulation models are often used to investigate dynamic effects and evaluate behavior of designed components. Like all models, they represent a simplification of the reality with focus on what seems relevant for the purpose of the model. The way and degree of this simplification decisively influence the quality of the model and through that the possible gain in knowledge. The simplifications are made by the design engineers, who assume the relevance of embodiment parameters and their relations to function fulfillment.

The major challenge in building up a simulation model lies in finding parameters that contribute to the investigated functions and the reduction of the parameters to a manageable level during the simplification. Identification of these function relevant parameters is often done implicitly and difficult to retrace. This leads to another challenge, the documentation of the process of finding these parameters, so others can comprehend the thoughts of the engineers who built the model.

For identification and documentation of function relevant parameters of the embodiment, the C&C²-Approach can help design engineers to find the relevant embodiment which is linked to the function fulfilment [1]. It can be seen as a language to explicitly describe embodiment function relations. However, the usage of C&C²-Approach to build up a simulation model to

Peer-review under responsibility of the scientific committee of the 28th CIRP Design Conference 2018.
10.1016/j.procir.2018.03.039

analyze dynamic system behavior, has not been investigated in a case study up to now.

1.1. The C&C^2-Approach: an approach to link a systems functionality to its embodiment

For the connection of functions and embodiment in technical systems, modeling approaches have been developed. The axiomatic design [2] provides a structured approach for system design, that comprises four domains (customer, function, design and process), where requirements and solutions are generated. Axiomatic design focusses on the whole product development and doesn't provide support for finding the relevant embodiment parameters for function fulfilment. The function behavior structure framework [3] describes fundamental processes in design and differentiates between function as requirements for the product, the expected behavior and the real behavior in relation to its structure. It can describe these relations, however its potential in analysis of unknown relations is limited, as it doesn't provide support for the thinking processes of the design engineers in this phases. Characteristics Properties Model / Property Driven Development (CPM/PDD) [4] describes characteristics as parameters, that can be influenced directly by the developer, and properties as system behavior parameters, who can be influenced through change of the characteristics. The visualization of function relevant embodiment as support for the thinking process of the design engineers however is not supported with the described approaches to model relations of embodiment and function in technical systems.

As design engineers use sketches, CAD-models, technical drawings and other visual representations of a system to understand a technical system, the C&C^2-Approach uses these illustrations as basis for modeling the relations of embodiment and function in technical systems.

The C&C^2-Approach was created by Matthiesen and Albers to help engineers to recognize function related parameters of the embodiment and support thinking in system context. It is a meta-model and consists of elements and rules to build up explicit models. The C&C^2-Approach can be compared to a language, that contains words and grammar to express knowledge. It consists of three key elements and three basic hypotheses, that define the usage of its key elements. Its key elements are the *Working Surface Pair* (WSP), C*hannel and Support Structure* (CSS) and the *Connector* (C). [5]

A WSP describes the interface, where parts of the system connect while it fulfills its function. The CSS runs through system parts and connects the WSP. A CSS can include parts of components or whole subsystems, according to the modeling purpose. The C sets the system boundary and transfers effects from outside the boundary into the system [6]. These elements contain parameters of the embodiment, that are relevant for the function fulfillment. For example a friction coefficient is a parameter of a WSP, the stiffness of a component or subsystem is a parameter of a CSS. These parameters cause the functions of a system and are therefore relevant for simulation models. The C&C^2-Approach supports the documentation of these parameters and their relation to functions in the system.

The basic hypotheses describes possibilities and boundaries of modeling with the C&C^2-Approach [5]. The first basic hypothesis states, that function always needs interrelations of components through WSP. The second basic hypothesis states that a function is fulfilled through a minimum of two WSPs, that are connected by a CSS and integrated in the environment by Connectors. The third basic hypothesis describes the fractal character of modelling and shows, how the created C&C^2-Model of a system differs according to point of view and purpose of modelling. These hypotheses are shown in Figure 2 right side.

Using the C&C^2-Approach, models of the investigated system are built up. These models are called C&C^2-Models and connect the investigated function to the design elements that cause it. To build up a C&C^2-Model, the technique that Matthiesen [1] describes, can be used, which is shown in Figure 1. For further details see also [7].

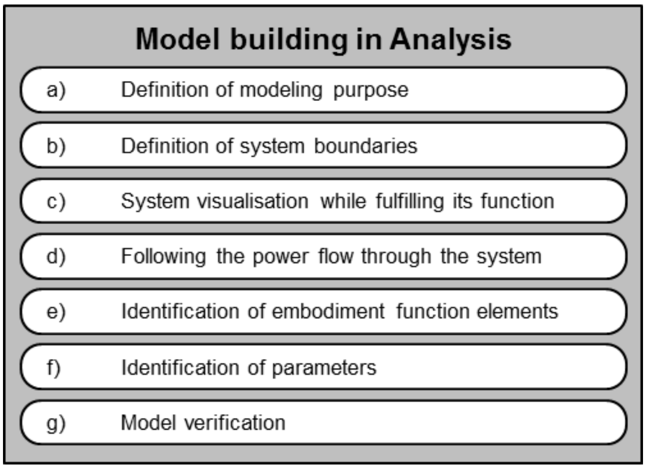

Figure 1: C&C^2-Model building according to [7]

At first the purpose of the model needs to be defined. This purpose helps to focus the model building. It is shown in Figure 2 on the bottom left side. After that, system boundaries are set up and states of the system are defined. A new state is defined when WSPs of the system disperse, are created, or when a CSS, WSP or C significantly changes its parameters. These states can be connected through a C&C^2-Sequence Model [8]. In Figure 2, the static view of the torque transmission needs only a system boundary of area, which is shown in the C&C^2-Model.

In the next step, a visual representation of the system while fulfilling its function must be found. In Figure 2, a rendered CAD cross section is chosen. The power flow through the system is analyzed and the key elements of the C&C^2-Approach are identified and visualized. From that, the function relevant parameters of the embodiment are identified. These parameters are left out for reasons of overview in Figure 2. They can be for example the length and torsional stiffness of CSS 1 and CSS 2 or the contact area of WSP1. With these parameters, a quantitative understanding of the systems functionality is possible. This will be used as basis for the simulation model. Finally the C&C^2-Model needs to be verified. To verify a C&C^2-Model, the assumed relations of identified embodiment parameters to the function fulfillment have to be tested. This can be done through design hypotheses, that connect an embodiment parameter with a function [9]. With the built up C&C²-Model, function relevant embodiment parameters are explicitly documented and can be used as a starting point for creating simulations. In this contribution the following research question will be addressed: How does the usage of the C&C²-Approach support the building process of a simulation model?

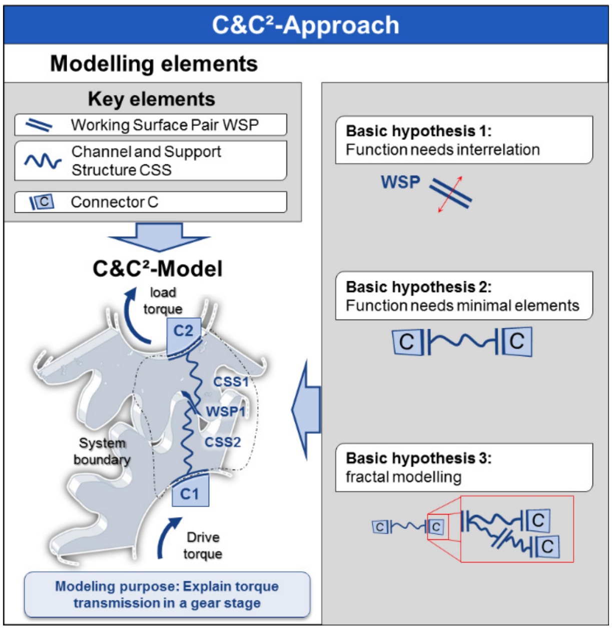

Figure 2: Components of the C&C²-Approach and their usage to create a C&C²-Model according to [7]

2. Materials and Methods

2.1. The Method: Single Case Study and semi-structured interview to gain qualitative findings

To answer the research question and investigate the usage of the C&C²-approach in the building process of a simulation model, a single case study was conducted. The test case was the analysis of a screw driver overload clutch model. Goal of the model building was to increase the understanding of the embodiment function relations of the system, focusing on the function *torque transmission* of the overload clutch. During the analysis process the C&C²-Approach was used. The test subject in the study was a design engineer who was already familiar with the C&C²-Approach and the basic functions of an overload clutch.

At the end of the study a retrospective semi-structured interview [10] was carried out with the design engineer. Its aim was to find out, how the design engineer had used the C&C²-Approach as support in the system analysis. The two main topics of the interview were the simplification of the system and the documentation process of the embodiment function relations.

2.2. The Case: Development of an overload clutch model

Using the example of an electric screwdriver, a simulation model is needed to investigate the dynamic behavior of its overload clutch. The overload clutch prevents the screw from damaging the wood workpiece through excessive torque loading. This overload clutch is integrated in the ring gear of the planetary transmission and is shown in Figure 3. It limits the torque from the engine to a set value, that is regulated through preload of springs on the clutch. When the torque is lower than the set value, the clutch is closed and the ring gear doesn't move. The sun gear transmits the torque and rotation to the planet carrier, that is connected to the output shaft. When the torque at the output shaft is higher than the torque limit, the clutch opens and the ring gear moves. The planet carrier stands still and the torque and rotation is transmitted from the sun gear to the ring gear. This concept of the clutch causes vibrations of the power tool and dynamic torque change at the screw while limiting the torque.

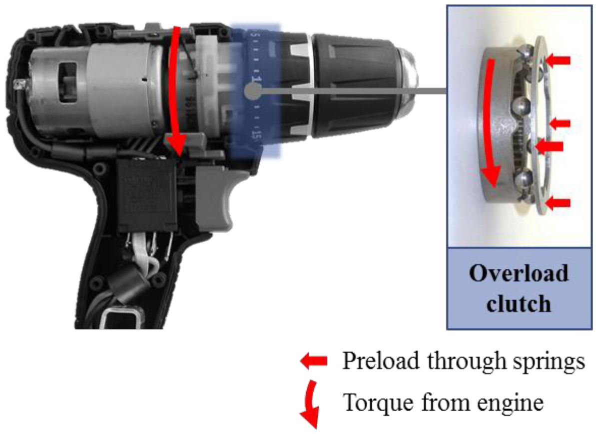

Figure 3: Overload clutch in the electric screw driver according to [11]

When design engineers want to improve the electric screw driver, for example towards higher application comfort, they need to understand the relation between function and embodiment. The quality of function fulfilment of the overload clutch is influenced by the function relevant parameters of the embodiment. Design engineers can only influence the function of a system through the embodiment and its parameters [7].

Figure 4 shows a detailed view of the overload clutch. It consists of the clutch ring, six balls, six springs that preload two spring rings, and the housing.

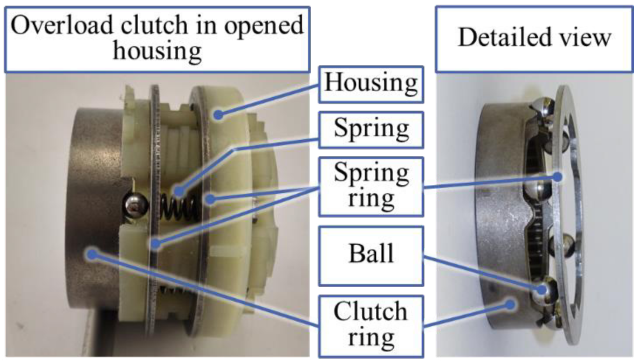

Figure 4: Components of the overload clutch

The function of interest, in the study, is the dynamic *torque transmission* of the system overload clutch. When the torque is lower than the set torque limit, the overload clutch blocks the movements between the housing and the clutch ring, which is also the ring gear of the planetary transmission. When the torque is higher than the torque limit, the balls lift the spring ring, which allows movement between housing and clutch ring. The clutch moves and no torque is transmitted to the output shaft.

The objective of the analysis was to define the requirements that have to be met by the simulation to being able to investigate the dynamic system behavior.

3. Results

3.1. Modelling the overload clutch with the C&C²-Sequence Model

The described results of the analysis are based on the retrospective interview and analysis of the documentation that was created during the project . The analysis of the power tool overload clutch was started by defining a purpose for the C&C²-Model. That purpose was to identify the embodiment that influence the dynamic torque transmission of the clutch. Identified parameters of the embodiment can be integrated in the simulation model. They build up the basis for a simulation model. The system boundary of the area was defined around one of the balls and its surrounding components.By following the flow of forces the design engineer analysed which components and parameters within the system boundaries could be relevant for the function fulfillment. The assumption was that similar components behave similar and the system behavior can be investigated by modeling that part of the system. That is why the system boundary is set around as can be seen in Figure 5. Another assumption was that the behavior repeats every 60° in rotational angle of the clutch ring. This boundary of the angle of the overload clutch was then separated into 4 different states. For each state, a different C&C²-Model was necessary, as WSPs, CSSs and Cs appeared, were dispersed or changed their properties. These C&C²-Models were combined to a C&C²-Sequence Model, that is shown in Figure 5.

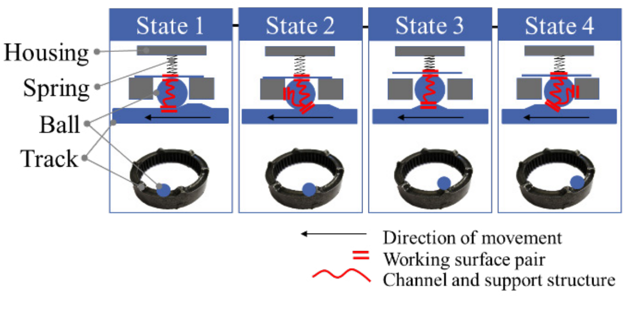

Figure 5: C&C²-Sequence Model (simplified), according to [11]

Here the four defined states and the simplified representation of the C&C²-Models in these states are visible. The Connectors are not represented for the purpose of a better overview. Further details of these states are described in [11], p. 6.

The four states of the C&C²-Sequence Model, the WSPs, CSSs and Cs were identified and documented. Then their parameters were specified. Figure 6 shows a section of state 4 of the C&C²-sequence model, where parameters have been assigned to WSPs and CSSs. Out of the large number of existing paraternaries, the engineer only included those in the C&C model that, in his opinion, directly influence the fulfillment of functions.

For example the friction in WSP2 might influence the behavior of the spring and is therefore considered relevant for the dynamic system behavior.

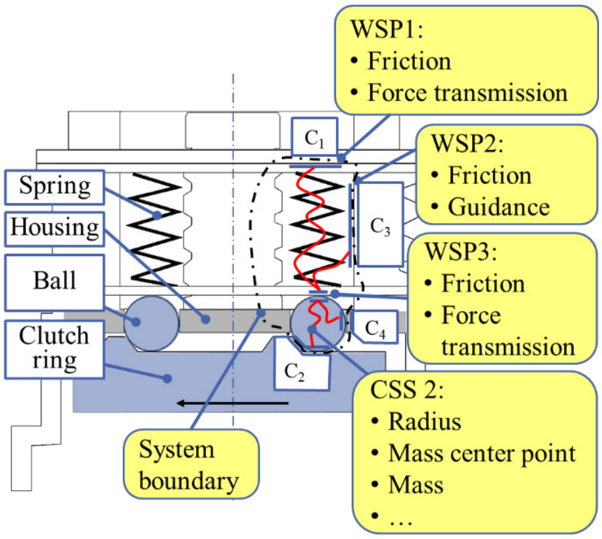

Figure 6: Detail of state 4 of the C&C²-sequence model according to [11]

The as relevant for the function identified parameters of the WSPs, CSSs and Cs were then implemented into a multi domain Simulation which is based on a physical structure. The Simulation was build in MATLAB® Simulink/Simscape to simulate the system behavior.

3.2. Results of the semi-structured interview with the design engineer

The interview with the engineer showed, that the C&C²-Approach was used as a structured analysis approach. The mental model of the relation of embodiment and function was transferred to and documented by the engineer as a C&C²-Sequence Model. During the analysis the simplification was supported by focusing on the investigated function. The design engineer had the following question in mind: „Which element is involved in the function fulfillment and if it is involved, how is it involved?“

Another example is the angle of the track in State 2 that was rated by the engineer as important for the load that can be transmitted by the WSP between the track and the ball.

Focusing on one of the major challenges, the simplification of the technical system was described as supported by following the flow of forces.

Another mentionend fact that supported the simplification, was the structuring of the system in WSPs, CSSs and Cs. Furthermore, relevant parameters were assigned to the C&C²-Elements. For example the design engineer assigned the mass center point of the ball as relevant for the torque transmission to the CSS 2. The characteristics of the ball itself were rated as not important for the function fulfillment and therefor not omitted in the later model. In this clutch, the supporting forces are realized by a spring. Following the C&C²-Approach the engineer included the surrounding components and their interaction with the overload clutch into the analysis and the C&C²-Model. The embodiment of single components, like the track, the balls and the housing were analyzed in detail.

The division into different states through the C&C²-Sequence Model was mentioned positively by the engineer. One statement was: „You consider what happens and changes in the different states.“ For the design engineer the states lead to case differentiation in the later simulation model. Changes of the value of the parameters within the states also needed to be implemented in the following simulation model.

Also the design engineer supported the authors claim, that the documentation of relations of embodiment and function as well as function relevant parameters in a C&C²-model can be helpful for communication with other project members. The statement was: „The presentation of the C&C²-Model contains the results of the analysis. And it also contains what needs to be implemented in the simulation.“ Furthermore, it was mentioned that it was possible to easily transfer the created C&C²-Model into the simulation environment MATLAB® Simulink/Simscape.

4. Discussion

The semi structured interview showed, that using the C&C²-Approach during the regarded project was considered helpful in the process of building up a simulation model in the aspects of identification of function relevant parameters and documentation of thoughts. In the following section the statements/results are discusses with regard to the described challenges:

4.1. Simplification - Reflection on the Approach of the Design Engineer

The desgn engineer analyzed the flow of forces and the components within the system boundaries using the C&C²-Approach. Subsequently the parameters, relevant for fulfilling the function, were selected and abstracted. For instance the ball as a component is insignificant for the function fullfilment, according to the design engineer. However, knowledge about the displacement of the mass center point of the ball is relevant for compression of the spring and therefore relevant for the torque limitation and the characteristics of the clutch release. The approach encouraged the engineer to focus on the function relevant embodiment through the setting of system boundaries and Connectors and defining WSPs and CSSs. The systems components have many parameters, but only the ones that, according to the design engineer, influence the function torque transmission are documented in the C&C²-Model. This leads to a function focused simplification of the real overload clutch.

4.2. Documentation – Reflection on the Approach of the Design Engineer

Dividing the dynamic behavior into different states the engineer created different C&C²-Models of the system. In the interview, the engineer pointed out that the C&C²-Approach supported the division of the systems behavior into different states. Since the engineer has created a new C&C²-Model for each state and has defined the relevant parameters, it is clearly displayed when new parameters are added or omitted during the function fullfilment.

Using the C&C²-Approach the design engineer explicated his mental model into an explicit and documented C&C²-Model. The C&C²-Model represents the design engineers mental model of relations of embodiment and function. This documentation can be used for consultations with other engineers and is helpful if adjustments in the simulation are necessary. In case of false results, individual hypotheses that lead to a reduction of relevant parameters must be verified. For this purpose, the documentation of the C&C²-Model can be used. Thus the C&C²-Approach contributes to the expansion of the system understanding of the design engineer.

5. Conclusion

By using the C&C²-Approach and focusing on assignment of embodiment parameters to the C&C²-Elements, the design engineer has been supported in building up a simulation model of the overload clutch. The assumptions on the relation of embodiment and function were explicitly documented and visualized which supported the analysis and reproducibility of the simulation model building process.

The relevant design elements of the overload clutch were analyzed and visualized by highlighting the volumes, surfaces and the parameters that contribute to the fulfilment of the torque transmission. Those parameters are used in the investigation of the dynamical behavior of the overload clutch through a simulation model.

To summarize, by using the C&C²-Approach the development of a simulation model of the overload clutch of the electric screwdriver was supported.

Further effects will be investigated with the developed simulation model to verify the simplifications.

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