Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 109 (2022) 701–706

www.elsevier.com/locate/procedia

32nd CIRP Design Conference

Considering Manufacturing in Functional Modelling – Case Study on Combination of Simulation-Driven Design with Design-for-Manufacture

Patric Grauberger[a]*, Tim Bruchmüller[a], Sebastian Zimprich[a], Sven Matthiesen[a]

[a]*IPEK – Institute of Product Engineering, Karlsruher Institute of Technology KIT, Kaiserstr. 10, 76131 Karlsruhe*

* Corresponding author. Tel.: +49 721 608 42798; fax: +49-721 608 46051. *E-mail address:* sven.matthiesen@kit.edu

Abstract

In engineering design, function fulfilment is the raison d'être of a product. However, economic boundary conditions have to be taken into consideration as well to enable marketability of the product. In this paper, a case study is presented, where function-based engineering using the Simulation-Driven Design is linked with Design-for-Manufacture as an example for economic design through qualitative modelling. The qualitative modelling with the Contact and Channel Approach aims to support the integrated consideration of functional requirements and manufacturing boundary conditions. The linked approaches are applied in the development of a test rig for hammer drills. It shows how Design-for-Manufacture can be considered early in conceptual decisions in embodiment design by separating functional embodiment and residual structure through qualitative modelling. The freeze-unfreeze strategy is presented as a possibility to identify potential for Design-for-Manufacture to meet economic boundary conditions in conceptual design without reducing the functionality of the system. Further research possibilities regarding qualitative modelling to support functional and economic design are uncovered.

Keywords: design engineering, Design-for-Manufacture, functional modelling, design methods, techniques and tools, Simulation-Driven Design

1. Introduction

In embodiment design, the product's embodiment has to be defined in a way that enables it to fulfil the desired functions [1]. Based on parameterized product definitions (e.g., through computer-aided design CAD) computer-supported optimization is possible through approaches like FEM simulation (finite element method, [2]). For conducting these optimizations, design engineers need knowledge about how the system works in detail and which parameters of the embodiment are relevant to its behaviour and functions. This can be achieved through functional modelling.

Approaches to functional modelling aim to support design engineers in reasoning about functionality and its relation to the embodiment as the carrier of functions [3]. They contain elements and structures for modelling these embodiment function relations (EFRs) on different levels of detail and for different purposes in engineering design.

2. State of the art

2.1. Functional modelling approaches in design

Functional modelling can be done by using different approaches. For example, the Axiomatic Design Theory [4] is widely used to describe activities in embodiment design and provides terms for modelling relations of functional requirements and design parameters. Characteristics Properties Modelling CPM [5] enables differentiation of design parameters into characteristics that can be influenced directly, and properties that can be seen as dependent variables. It also enables the integration of mathematical equations [6]. The Design Structure Matrix (DSM) is often used to support

10.1016/j.procir.2022.10.039

system decomposition and integration. Its advantage lies in the decomposition of highly complex systems into subsystems, which are easier to understand by design engineers [7].

All of the described methods and models need defined parameters as input. In defining the relevant parameters, design engineers need to connect the system's embodiment to its functions mentally [8]. This is often done implicitly (e.g., through expert workshops or by "taking a close look").

For supporting the mental processes in identifying function-relevant parameters, the Contact and Channel Approach (C&C²-A) can be used [9, 10]. As a qualitative modelling approach, it does not need defined parameters as input. Models built with the C&C²-A use arbitrary visualisation of technical systems from sketches to microscopic pictures, CAD cross-sections, or computer tomography pictures. This approach is described in detail in the following:

2.1.1. The Contact and Channel Approach – qualitative modelling approach in the case study

This section is based on Matthiesen et al. [11]. Parts of the following text are taken from that paper without changes.

The C&C²-A is a thinking tool for embodiment design. It aims to support design engineers in recognizing function-related parameters of the embodiment. It contains elements and rules to build up explicit C&C²-Models. It consists of three key elements and three basic hypotheses that define the usage of its key elements. An overview of the three key elements Working Surface Pair (WSP), Channel and Support Structure (CSS) and Connector (C) is depicted in Figure 1.

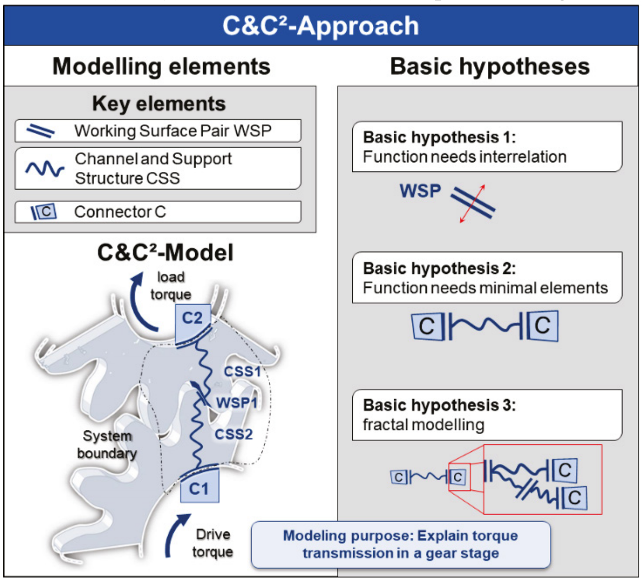


Figure 1: Overview of the C&C²-Approach and its elements [12]

A WSP describes the interface where parts of the system connect while it fulfils its function. The CSS goes through system parts and connects the WSP. A CSS can include parts of components or whole subsystems depending on the modelling purpose. The Cs represent a model of the surrounding systems and transmit influences from outside the system boundaries into the system [13]. The basic hypotheses describe the possibilities and boundaries of the modelling with the C&C²-A. They are depicted in Figure 1 (right side).

A C&C²-Model (Figure 1, centre) is derived by using the key elements and basic hypotheses. [11]

With the C&C²-A, qualitative EFRs can be described in a model as a basis for gaining quantitative insights and for further computer-supported optimization. This optimization can be done through e.g. Simulation-Driven Design, which can be seen as a process where decisions on the behaviour and performance of the embodiment are supported in all phases of the (design) process by computer-based product models and simulation. Simulation-Driven Design needs mathematical function descriptions (like equations of motion) to gain quantitative insights about EFRs and provide support in the identification of optimal parameter settings. [14]

2.2. Design approaches considering economic boundary conditions

Besides deriving an embodiment that enables function fulfilment, design engineers need to consider the given economic boundary conditions, lifecycle requirements, legal requirements, lot size, and many more factors. In this contribution, the focus is on costs emerging in the manufacturing process e.g. the effort of assembly and costs of components including manufacturing effort for specially produced components.

Approaches to support are the Design-for-X approaches that contain specific requirements and methods to implement them [15]. An approach related to the focus of this contribution is Design-for-Manufacture, which is supported by special principles and rules [16]. Design-for-Manufacture comprises all design principles for a production-oriented design of components and assemblies [17]. Together with Design-to-Cost, Design-for-Assembly and Design-for-Quality, it can be seen as a standard operation for concurrent simultaneous engineering [18].

Design-for-Manufacture aims at the detailed design of a chosen concept for minimal manufacturing costs and therefore depends on a defined concept for its application [19].

The joint consideration of EFRs gained in simulation and the effect of economic boundary conditions on the embodiment is a challenge for design engineers, as the necessary views on the system are different. In a simulation, the system is described as a set of optimizable properties from a functional point of view, while in the design of the embodiment, the system is seen as a set of components from a topological point of view [20]. Approaches like concurrent engineering [21] connect economic boundary conditions through manufacturing with design on the process level of product development. Approaches like Multidisciplinary Design Optimization (MDO) have also been extended to consider economic boundary conditions, for example from additive manufacturing [22].

Concluding, the available approaches consider either the detailed modelling of EFRs to enable the product's functions or the economic and other boundary conditions of the already designed product. Approaches that consider both aspects require parameterized products as a basis for computer-supported optimization and therefore are difficult to use in early embodiment design, where conceptual decisions have to be made (e.g. change the working principle instead of topology optimization). Approaches with a focus on product architecture can also consider both aspects, however, their aim does not consist in supporting detailed embodiment design.

3. Integrated consideration as aim of this contribution

From the presented state of the art the research question of this paper is derived:

How can qualitative modelling support consideration of functional requirements and manufacturing boundary conditions in conceptual decisions during early embodiment design?

To answer this question, a case study is set up, where Simulation-Driven Design is linked to consideration of economic boundary conditions from Design-for-Manufacture by using the C&C²-A as a qualitative modelling approach for EFRs. The linking of the three approaches is evaluated through application in the development of a test rig for hammer drills. This test rig aims to meet the demand for reducing uncertainties for high-quality test results early in embodiment design [23]. It contributes to the short development cycles of power tools emerging from short product life cycles [24]. In this development project, very high functional requirements have to be met as no such test rig exists up to now. The challenge here lies in designing a suitable embodiment for these requirements. Rigorous economic boundary conditions have to be considered as well.

4. Materials and methods for the case study

In this section, the methodical approach and the case study are described as a basis for the investigation.

4.1. Methodical approach

Simulation-Driven Design, Design-for-Manufacture and C&C²-A are combined and applied in the case study.

Simulation-Driven Design is used for the mathematical function descriptions and Design-for-Manufacture is used for meeting the economic boundary conditions. Currently, both approaches are stand-alone options but have the potential of being linked for an effective embodiment design process.

To link these approaches, the C&C²-A is used, which enables design engineers to identify embodiment relevant to desired functions and decide which embodiment parts can be changed to use Design-for-Manufacture. The linking element is the freeze-unfreeze-strategy. An overview is given in Figure 2.

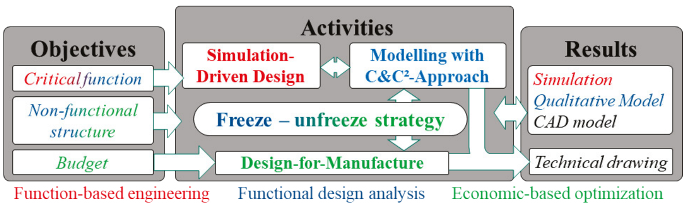


Figure 2: Overview of the combined approaches applied in the design activities

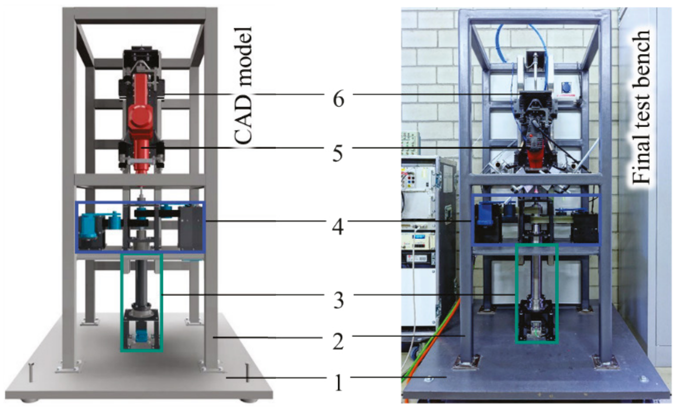
In the evaluation of this proposal, success is measured through two variables: firstly, keeping within the project budget and secondly, reaching the aimed-for precision in the validation according to Bruchmueller et al. [23].

4.2. The development project as basis for the case study

The test rig for hammer drills aims at reducing testing costs by replacing user and concrete in the design evaluation during validation. The main functionalities of the test rig are the application of an equivalent drilling torque and impact characteristics regarding the hammer drilling concrete. This distinguishes the test rig from the steel ball energy absorber outlined in ISO 28927-10 [25]. In a previous study, the drill bits impact characteristics was determined using the Coefficient of Restitution (CoR) [23]. The CoR is calculated by the drill bits relative absolute velocity prior to the impact divided by the relative absolute velocity after the impact. The functional requirements on the test rig were as follows:

- Implement quantitative hammer drill characteristics: 2.6 J single impact energy, 720 W nominal power, Drilling torque: 0.27 Nm
- Drill vertically downwards
- Replace the user by a Hand-arm model based on Jahn and Hesse [26].
- Reuse the existing drill holder, ensure low manufacturing time, use standard components.
- Implement a Coefficient of Restitution of 0.5 as the critical function

Figure 2 displays the test rig developed for hammer drills. A main frame (2) and the impact simulation device (3) rest on a base plate (1). The drilling torque simulation device (4) is connected to the main frame (2). The hammer drill (5) is connected to the input shaft of the drilling torque simulation device and connected to the hand-arm model (6). The hand-arm model is a dual-mass oscillator combined with a pneumatic cylinder. The dual-mass oscillator represents the dynamic properties of the human arm; the pneumatic cylinder applies the push forces to the hammer drill. The hand-arm model is connected to the main frame (2).



1	Base plate		4	Drilling torque simulation device
2	Main frame		5	Hammer drill
3	Impact simulation device		6	Hand-arm model

Figure 3 Test rig developed for hammer drills adapted from [27]

5. Results

In the following, the linking of the models is described on a theoretical basis through the three activities *function-based engineering*, *functional design analysis* and *economic-based optimization*. Then the three activities are shown as conducted in the case study.

5.1. Linking the models – theoretical basis

The objective of *function-based engineering* is the synthesis of the critical function. This function is derived from the requirements, where design engineers need to evaluate which requirement contains the most critical function. With the use of modelled EFRs and Simulation-Driven Design, a simulation model and an initial CAD model of the embodiment are derived. The simulation model contains the relations of the embodiment with the physical behaviour using mathematical equations for the functional description.

The main objective of the subsequent *functional design analysis* is the freeze-unfreeze strategy. It contains identification and evaluation of the design, concerning areas and features with no direct relation to the critical function. Using the C&C²-A, the design is separated into CSSs and residual structures. A design freeze of the embodiment directly contributing to the critical function (modelled in a C&C²-Model) is done. With an unfreeze of the residual structure (components not modelled in the C&C²-Model), the design is optimized for manufacturing and budget-related costs in the economic-based optimization. Here, Design-for-Manufacturing guidelines are implemented. Examples of these guidelines are "minimize the total number of parts", "use standard components", or "avoid separate fasteners" [16].

This freeze-unfreeze strategy allows design engineers to determine the design space for optimization regarding economic boundary conditions without compromising the function-related requirements. The only prerequisite for this strategy is knowledge about which embodiment is related to the critical function. This enables economic-based optimization early in embodiment design, as there is no need for a fully defined product.

With the determined optimization potential, *economic-based optimization* takes place. The aim of this activity is the synthesis regarding economic boundary conditions, such as the budget. Using the method of Design-for-Manufacture, the residual structures are optimized for production-ready design. For example, the frame configuration can be shifted to enable welding of the supporting beams that otherwise have to be fastened with screws and angles. When the economic-based optimization is done, the next functions can be considered in function-based engineering.

5.2. Case study step 1: Function-based engineering

In this section, the activities *function-based engineering*, *functional design analysis*, and *economic-based optimization* are applied in the case of the development of the test rig.

The critical function CoR– value 0.5 - (see Section 2.2) is the desired behaviour of the impact simulation device. Using the Simulation-Driven Design, the CoR was used to calculate the system's required stiffness and damping parameters, using a mass oscillator as a model approach [28]. This mass oscillator is solved analytically with the described boundary conditions CoR, impact frequency, mass and the velocity prior to the impact. The solution leads to the required stiffness parameter k = 34,385,190 N/m and the damping parameter d = 1,381 Ns/m.

Since a single machine element cannot fulfil the required stiffness and damping parameters, the critical function is realized by a concept combining a cast iron cylinder and a ring spring. The cast iron provides a high material damping and mass, the ring spring shows a high damping rate. Since this non-linear system cannot be solved analytically anymore, a MATLAB/Simscape® [29] simulation model containing the relevant stiffness, mass, and damping parameters was composed. By this simulation model, a CAD model was refined. Figure 3 displays the EFRs using Simulation-Driven Design. The CAD model on the right and the simulation model on the left consist of the same sub-structure. The parameters (mass, stiffness, or damping) of the design change in the CAD model are transferred into the simulation model. An analysis (blue arrow) is conducted, and the resulting CoR is compared to the required value. In an iterative optimization of the critical function (CoR too high or too low), stiffness, mass, and damping parameters were changed and the design changes were also implemented in CAD (synthesis, green arrow). The critical EFR of the CoR is shown in Figure 3 using the example of the cast iron cylinder's length and diameter. These two parameters influence the moving mass to a high degree and, therefore, the CoR. The loop was carried out until the CoR matched the required value of 0.5 and the design freeze was set.

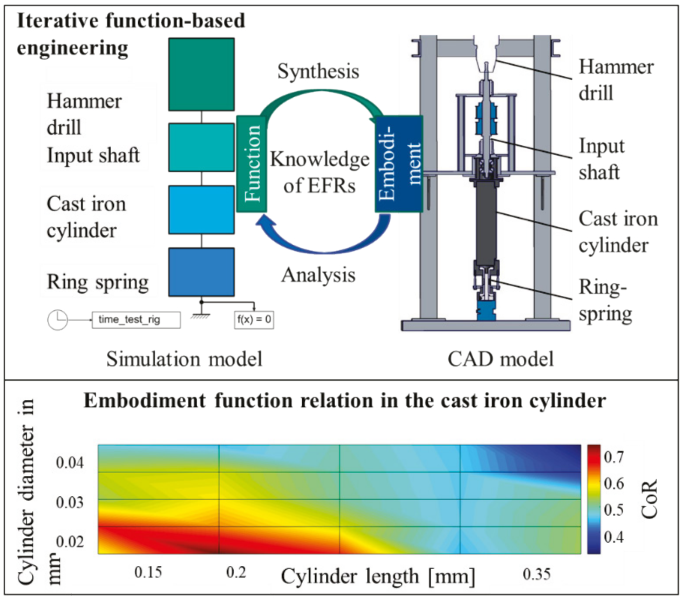


Figure 4 Simulation-Driven Design – Simulation results and CAD model, adapted from [27]

5.3. Case study step 2: Functional design analysis

Using the C&C²-A, the test rig design is investigated for the residual structure regarding the critical function CoR. This residual structure is not a global residual structure that can be removed completely but contains parts of the system that have no or less influence on the CoR. Figure 4 displays the residual structure as parts of the main frame, base plate, and bearing arrangement of the input shaft and the pre-load of the ring spring.

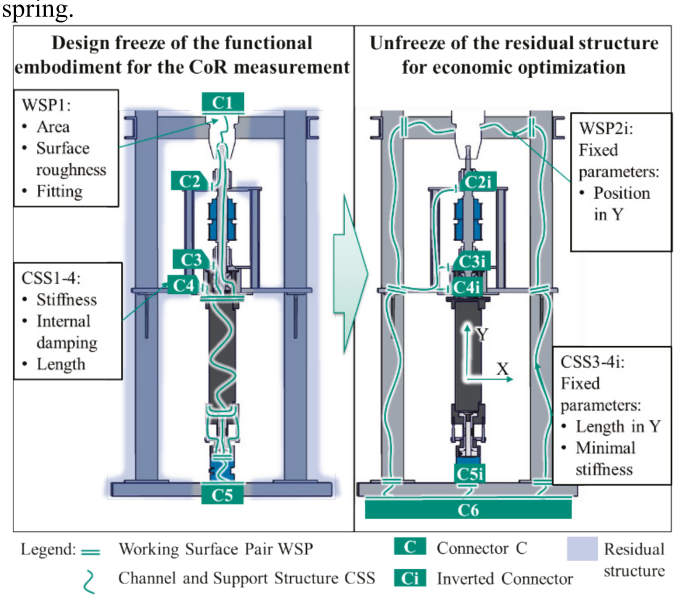


Figure 5 Design space for optimization

Its identification as the residual structure is possible through purpose-bound modelling with C&C²-A. For the purpose of "identify EFRs that influence the CoR" (Figure 4, left side), all other sub-functions beside the one relevant to the desired system behaviour leading to the CoR, are seen as secondary functions and are not modelled. The identified residual structure only contributes to the CoR through position information in the Connectors C2-C4 but is necessary for the system to work through the fulfilment of various secondary functions. The Connectors are inverted and the main frame connection can be optimized concerning the economic boundary conditions as long as the position information is still transmittable through the Connectors. This activity is called unfreezing the main frame for the following economic optimization.

5.4. Case study step 3: Economic-based optimization

In order to match the economic boundary conditions, methods of Design-for-Manufacture are applied. Figure 5 displays the evolution of the main frame. The functional design for the integration of the simulation devices is on the left; the optimized design is on the right. In an iterative optimization for economic boundary conditions, the design is investigated for potential in equalization, weldability, and reduction of used parts. As a result of equalization, only square tubes with the same cross-section are used. To enable welding and therefore reduce the use of sophisticated connection elements, the distance between the tubes is increased to enable an increased operational radius during welding. The sled guidance for the power tool was designed using many parts, which are replaced by a much heavier but simpler design on one side of the sled. Even though no exact numbers on the economic effect can be given, the measures reduced the overall costs (e.g. cheaper square tube instead of U-profile and quantity discount results in ~50% reduced material costs for the frame) and effort (welding in the inhouse-workshop is possible with the new design) needed to build it up.

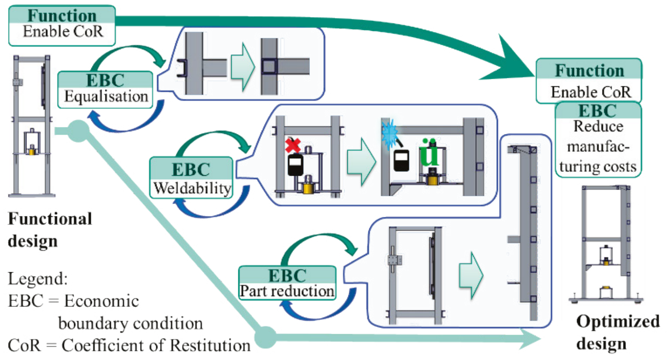


Figure 6 Economic-based engineering using Design-for-Manufacture

The result of the case study is a test rig with 90 % accuracy concerning hammer drilling concrete [23] enabling up to now not possible investigations of the hammer drill.

6. Discussion

Application of the C&C²-A in *functional design analysis* enabled identification of residual structure. The optimization space was determined without compromising the functional requirements. Using Design-for-Manufacture in the *economic-based optimization*, the budget requirements are met.

In the case study, the freeze-unfreeze strategy as decision support led to a high grade of fulfilment for the critical function in a challenging development project. This strategy enabled *economic-based optimization* with Design-for-Manufacture early in the embodiment design phase without interfering with the critical function.

To enable the critical function, highly unknown EFRs had to be implemented into a product with a manageable amount of components and interactions. It was also developed for early embodiment design where often no powerful executable models of the product exist.

Its applicability can be seen as focused on small-batch products with high-end functionality and large changes in function principles compared to the predecessor product. In redesign with small changes, it might not be the best choice. It might also not be supportive in projects, where optimization of the critical function is aimed at, as there, the residual structure is mostly not in the focus of the design engineers. Another challenge in engineering practice, especially in mass production, is the target costing. For this, other approaches exist, that can be used in conceptual design (e.g. [30]).

Whether the integration of other methods than the ones chosen can extend or change the support in consideration of functional requirements and economic boundary conditions in different projects has not been investigated.

Another limitation is the study design as a single case study, hence no general statement can be derived about success criteria regarding its usability or applicability for design engineers. In addition, factors like modelling experience could have led to project success without being identified. It might be that developers who are not familiar with the C&C²-A experience difficulties in identifying residual structures by using this approach.

7. Conclusion and Outlook

In this contribution, a case study for integrated consideration of manufacturing in functional modelling is presented at a development project of a hammer drill test rig. The objectives of costs and functionality were reached using qualitative modelling with the Contact and Channel Approach. The freeze-unfreeze strategy was developed for linking functional and economic design. As the next step, variables and success criteria of the freeze-unfreeze strategy are to be operationalized for further investigation. For example, more objective measurements for the effectiveness of this strategy are needed. Here, it will also be investigated how developers, who are not familiar with the Contact and Channel Approach, are able to work with it. This lays the basis for experimental evaluation, which can provide more reliable data.

Another aim of future research will be the investigation of different approaches to functional modelling and the use of their descriptions for embodiment function relations. This can extend the support in connecting Simulation-Driven Design and Design-for-X methods in embodiment design phases at a later stage.

References

[1] S. Matthiesen, "Gestaltung - Prozess und Methoden," in *Pahl/Beitz Konstruktionslehre*, B. Bender and K. Gericke, Eds., 9th ed., Berlin Heidelberg, Germany: Springer-Verlag GmbH, 2021.

[2] S. Vajna, C. Weber, K. Zeman, P. Hehenberger, D. Gerhard, and S. Wartzack, *CAx für Ingenieure: Eine praxisbezogene Einführung,* 3rd ed. Berlin, Germany: Springer Vieweg, 2018.

[3] B. Eisenbart and M. Kleinsmann, "Implementing shared function modelling in practice: experiences in six companies developing mechatronic products and PSS," *Journal of Engineering Design*, vol. 28, 10-12, pp. 765–798, 2017, doi: 10.1080/09544828.2017.1395395.

[4] N. P. Suh, "Axiomatic Design Theory for Systems," *Research in Engineering Design*, vol. 10, no. 4, pp. 189–209, 1998, doi: 10.1007/s001639870001.

[5] C. Weber, "Modelling Products and Product Development Based on Characteristics and Properties," in *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations*, A. Chakrabarti and L. T. M. Blessing, Eds., London, s.l.: Springer London, 2014, pp. 327–352.

[6] R. B. Malmiry, J.-Y. Dantan, J. Pailhès, and J.-F. Antoine, "A product functional modelling approach based on the energy flow by using characteristics-properties modelling," *Journal of Engineering Design*, vol. 27, no. 12, pp. 817–843, 2016, doi: 10.1080/09544828.2016.1235261.

[7] S. D. Eppinger and T. R. Browning, *Design structure matrix methods and applications*. Cambridge, Mass, USA: MIT Press, 2012.

[8] S. Matthiesen, "Seven Years of Product Development in Industry - Experiences and Requirements for Supporting Engineering Design with 'Thinking Tools'," in *Proceedings of the 18th International Conference on Engineering Design*, Copenhagen, Denmark, 2011, pp. 236–245.

[9] A. Albers and E. Wintergerst, "The Contact and Channel Approach (C&C²-A): relating a system's physical structure to its functionality," in *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations*, A. Chakrabarti and L. T. M. Blessing, Eds.: Springer, 2014, pp. 151–172.

[10] P. Grauberger, H. Wessels, B. Gladysz, N. Bursac, S. Matthiesen, and A. Albers, "The contact and channel approach – 20 years of application experience in product engineering," *Journal of Engineering Design*, 1466-1837, 2020, doi: 10.1080/09544828.2019.1699035.

[11] S. Matthiesen, P. Grauberger, and L. Schrempp, "Extended Sequence Modelling in Design Engineering – Gaining and Documenting Knowledge about Embodiment Function Relations with the C&C²-Approach," *In: Proceedings of the Design Society: International Conference on Engineering Design*, vol. 1, no. 1, pp. 1483–1492, 2019, doi: 10.1017/dsi.2019.154.

[12] S. Matthiesen, P. Grauberger, C. Sturm, and M. Steck, "From Reality to Simulation – Using the C&C²-Approach to Support the Modelling of a Dynamic System," in *Procedia CIRP*: vol. 70, pp. 475–480: Elsevier B.V., 2018.

[13] B. Gladysz and A. Albers, "How Do C&C²-Models Improve Efficiency, Comprehensibility and Scope in Failure Analysis-An Empirical Study Based on Two Live-Labs," in *DS92: Proceedings of the DESIGN 2018 15th International Design Conference*, Dubrovnik, Croatia, 2018, pp. 1127–1138.

[14] U. Sellgren, "Simulation-Driven Design - Motives, Means, and Opportunities," PhD-Thesis, The Royal Institute of Technology, Stockholm, Sweden, 1999.

[15] G. Q. Huang, Ed., *Design for X: Concurrent engineering imperatives*. Dordrecht, Springer Netherlands, 1996.

[16] H. W. Stoll, "Design for Manufacture: An Overview," *Appl. Mech. Rev.*, vol. 39, no. 9, p. 1356, 1986, doi: 10.1115/1.3149526.

[17] G. Boothroyd, P. Dewhurst, and W. Knight, *Product Design for Manufacture and Assembly*. Boca Ranton FL: CRC Press, 2002.

[18] H.-J. Bullinger and J. Warschat, Eds., *Concurrent Simultaneous Engineering Systems: The Way to Successful Product Development*. London: Springer London, 1996.

[19] K. L. Edwards, "Towards more strategic product design for manufacture and assembly: priorities for concurrent engineering," *Materials & design*, vol. 23, no. 7, pp. 651–656, 2002.

[20] A. M. Maier, M. Kreimeyer, U. Lindemann, and P. J. Clarkson, "Reflecting communication: a key factor for successful collaboration between embodiment design and simulation," *Journal of Engineering Design*, vol. 20, no. 3, pp. 265–287, 2009, doi: 10.1080/09544820701864402.

[21] B. Prasad, F. Wang, and J. Deng, "Towards a Computer-Supported Cooperative Environment for Concurrent Engineering," *Concurrent Engineering*, vol. 5, no. 3, pp. 233–252, 1997, doi: 10.1177/1063293X9700500304.

[22] X. Yao, S. K. Moon, and G. Bi, "A Cost-Driven Design Methodology for Additive Manufactured Variable Platforms in Product Families," *J. Mech. Des*, vol. 138, no. 4, 2016, doi: 10.1115/1.4032504.

[23] T. Bruchmueller, N. Huegel, S. Wacker, and S. Matthiesen, "Modelling of Tool Workpiece Interactions—Coefficient of Restitution for Hammer Drilling of Concrete," *Forsch Ingenieurwes*, vol. 8, no. 1, p. 107, 2018, doi: 10.1007/s10010-018-00293-7.

[24] S. Matthiesen, S. Mangold, and T. Bruchmueller, "The influence of variating passive user interactions on power tools in the context of product development," *Forsch Ingenieurwes*, vol. 82, no. 2, pp. 157–168, 2018, doi: 10.1007/s10010-018-0269-x.

[25] *Hand-held portable power tools — Test methods for evaluation of vibration emission — Part 10: Percussive drills, hammers and breakers*, ISO 28927-10, ISO, Berlin, 2011.

[26] R. Jahn, M. Hesse, "Applications of hand-arm models in the investigation of the interaction between man and machine. In: Scand J Work Environ Health 12 (4 Spec No), S. 343–346. DOI: 10.5271/sjweh.2132.

[27] T. Bruchmüller, *Realitätsnahe und reproduzierbare Randbedingungen in der Vibrationsanalyse - Ein Ersatzuntergrund für elektropneumatische Bohrhämmer*, Doctoral thesis, Karlsruhe Institute of Technology, Karlsruhe, 2020

[28] E. Golysheva, *Hand-held electro-pneumatic percussion machine with reduced vibration emission*, Doctoral Thesis, Loughborough University, Loughborough, 2003.

[29] *Matlab® Simscape*: The Mathworks, Inc., 2017.

[30] A. Albers, S. Matthiesen, S. Revfi, C. Schönhoff, P. Grauberger and J. Heimicke, "Agile Lightweight Design - The Extended Target Weighing Approach in ASD - Agile Systems Design Using Functional Modelling with the C&C2-Approach" Proceedings of the Design Society: International Conference on Engineering Design, pp 2667-2767, 2019, https://doi.org/10.1017/dsi.2019.27

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.