



Linking product modelling approaches for an early consideration of vibration behaviour in embodiment design

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Abstract

It is essential to consider the vibration behaviour of a technical system as early as possible in the product development process. While quantitative product modelling approaches can provide detailed analyses on vibration behaviour, their early applicability is limited due to necessary information. In contrast, early applicable qualitative product modelling approaches in embodiment design fall short in considering the vibration behaviour. Therefore, this publication's objective is to investigate whether a qualitative product modelling approach focused on embodiment function relations can be linked with a product modelling approach considering the vibration behaviour. This investigation was carried out by intending to link the Contact & Channel Approach (C&C²-A) and Single Degree of Freedom (SDOF) system approach as exemplary product modelling approaches, and subsequently evaluating whether they provide an accurate insight into a design problem in comparison to experimental findings. The results show that a link from the SDOF system approach to the C&C²-A is possible and that this linking possibility can enable accurate qualitative insights into the vibration behaviour for a targeted manipulation of design parameters. Thus, the linked product modelling approaches are more capable together than the previous individual ones and represents a first step towards an early applicable consideration of vibration behaviour in embodiment design.

Keywords Design research · Product modelling · Product representation · Vibration behaviour · Embodiment design

1 Introduction

In today's dynamic technical systems, it is essential to take the vibration behaviour into account, as undesirable or unexpected vibration behaviour can lead to severe outcomes. These outcomes can affect both the systems themselves, as well as the people who interact with them. For example, these outcomes include damage or system failure, such as cracks in the blades of gas turbines (Leong 2008; van der Seijs et al. 2016; e.g., Hao et al. 2025), as well as increased vibration strain to operators using handheld systems, which can lead to musculoskeletal disorders (Griffin 1990; Nilsson et al. 2017; e.g., de Kok et al. 2019). Resolving these issues can involve costly iterations, particularly if they are

identified late within a product development process. Hence, to avoid time-consuming and costly iterations in the product development process due to the vibration behaviour, it has to be considered at an early stage (cf., Buur and Andreasen 1989; Tan et al. 2017).

Key design decisions affecting the resulting vibration behaviour of the system are made during the transition from the product concept to the initial design, known as embodiment design. Pahl and Beitz (1996, p. 199) define the embodiment design as "[...] that part of the design process in which, starting from the working structure or concept of a technical product, the design is developed, in accordance with technical and economic criteria and in the light of further information, to the point where subsequent detail design can lead directly to production [...]." Since a working prototype is rarely available at this stage, product models are used to support the design decisions. The relevance of product models in supporting design decisions is continuously discussed in the literature (Eckert et al. 2017; Maier et al. 2017; e.g., Eckert and Hillerbrand 2022; Weaver et al. 2024). Thereby, the product models used

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during embodiment design need to consider the influences resulting from vibration behaviour as early as possible to support appropriate design decisions.

The term product model (sometimes also referred to as design or artefact model) is used in this publication to refer to “a human-made, pragmatic, reductive representation of a technical product carrying attributes similar to the modeled original for the purpose of depicting its function, behavior, or structure, or for analyzing its behavior” (Paehler and Matthiesen 2024, p. 1). This term thereby always refers to a created product model of a specific technical product or system. In this regard, the term product model differs from the term product modelling approach, which is not specific to an individual technical product or system as the product model isn’t created yet (cf., Andreassen et al. 2015; Grauberger et al. 2020). The product modelling approach describes, among other things, the basic elements for modelling, the steps involved in modelling, and established rules, which are identical across multiple created product models of different technical products. For example, the product modelling approach of the Design Structure Matrix is described by Eppinger and Browning (2012) in terms of the structure of the matrix representation, how relationships within the technical system are represented in this matrix, the steps involved in creating it, and its purpose. In Wilschut et al. (2018), on the other hand, the product model, the created Design Structure Matrix of a floodgate, which was created by applying the steps of Eppinger and Browning (2012), is discussed and compared to another Design Structure Matrix. In design research, product modelling approaches are continuously being developed and refined so that they can be made available for engineering designers.

There are various product modelling approaches available in the current state of research for considering the vibration behaviour of technical systems (Sturm et al. 2019). The Multi Degree of Freedom (MDOF) system approach (Meirovitch 1986; e.g., Gardonio et al. 1997), Multi-body Simulation (MBS) (e.g., Rahnejat 2000), and Finite Element Method (FEM) (e.g., Mukhopadhyay 2021; Zhang and Wang 2024) are particularly widespread product modelling approaches in this context. These enable a detailed quantitative analysis of the vibration behaviour of technical systems. For example, the vibration response to a given excitation and the natural frequency can be determined. But to use these product modelling approaches, a fair amount of information is necessary, for example, about the geometry of the technical system, material behaviour, damping properties, and vibration characteristics (e.g., Firouzian-Nejad et al. 2017; Sturm et al. 2020). Without this information, time-consuming experiments or preliminary assumptions have to be made to substitute the missing information. Therefore, using these product modelling approaches requires time,

or their use is only possible at a later stage in the product development process. This poses a considerable challenge with regard to the early consideration of vibration behaviour in embodiment design. Hence, although these quantitative product modelling approaches can provide detailed analyses on vibration behaviour, their early applicability in embodiment design is restricted.

For embodiment design, a wide range of product modelling approaches is available, as shown in the literature reviews by Matthiesen et al. (2019) and Weidmann et al. (2017). These approaches identified in the literature reviews address various purposes, such as managing the design with a product architecture (e.g., Pahl et al. 1996), synthesizing alternative product concepts by representing their physical causalities (e.g., Rihtaršič et al. 2012; Sarkar et al. 2017), defining the design with the Design Structure Matrix (e.g., Eisenbart et al. 2017; Baylis et al. 2018), and enabling new insights with the Contact and Channel Approach (C&C²-A) or the Working Space Model (e.g., Beetz et al. 2018; Grauberger et al. 2020). In contrast to the quantitative approaches for considering vibration behaviour discussed in the previous paragraph, the available qualitative product modelling approaches focused on embodiment function relations can be applied early on in embodiment design, when the available information is still very limited. Examples include the symbolic representations, sketches, C&C²-A, and Working Space Model (Matthiesen and Grauberger 2024). Though, these product modelling approaches do not take vibration behaviour into consideration sufficiently. While they are able to indicate parameters of the embodiment that possibly influence the vibration behaviour, they do not enable the embodiment to be changed in a way that results in a targeted change in the vibration behaviour (Sturm et al. 2020; Hemmerich et al. 2025). Therefore, with regard to the support of early design decisions, they fall short in terms of considering the influence of the embodiment on vibration behaviour.

The problem is therefore that the early consideration of vibration behaviour in embodiment design is hindered, as the product modelling approaches for considering vibration behaviour are limited in their early applicability, while the early applicable product modelling approaches in embodiment design fall short in considering vibration behaviour. This neglect can lead to costly late iterations due to undesirable or unexpected vibration behaviour. Therefore, the limitations of the individual product modelling approaches shall be overcome.

1.1 Research objective and question

The research objective is to investigate whether a qualitative product modelling approach focused on embodiment function relations can be linked with a product modelling

approach considering the vibration behaviour. Doing so shall overcome the product modelling approaches' limitations and thereby facilitate the early consideration of qualitative vibration behaviour during embodiment design with limited available information. Therein, although the consideration of qualitative vibration behaviour is to be less precise than the described quantitative approaches, qualitative modelling can be advantageous for initial assessments due to them requiring less information, thereby being possible earlier and costing very little time.

The investigation is to be carried out using two exemplary product modelling approaches: The Contact & Channel Approach (C&C²-A) is chosen as product modelling approach for qualitative embodiment function relations, and the Single Degree of Freedom (SDOF) system approach is used as product modelling approach for considering vibration behaviour. The C&C²-A is chosen for its early ease of use in embodiment design and low requirements for the available information, and the SDOF system approach is chosen for being a simpler prelude to the established Multi Degree of Freedom system. Therefore, the following research question is derived:

How can a link between C&C²-A and SDOF system approach be established so that the insights regarding vibration behaviour can be incorporated into qualitative embodiment function relations modelling?

The research objective and question are inspired by early robust design, in which cost-intensive, late iterations due to robustness problems are to be avoided by shifting the focus of robustness considerations from late simulations and experiments to the early product concepts with the support of appropriate qualitative models and associated methods (Jugulum and Frey 2007; Eifler and Howard 2018; Li et al. 2026).

The following subsections therefore begin by presenting the fundamentals of the two product modelling approaches, C&C²-A and SDOF system approach (see Sect. 1.2 and 1.3). Section 2 then outlines the method used to investigate the possibility of linking the product modelling approaches, which is based on building the models for a common design problem, using an angle grinder as an example system. The results are presented in Sect. 3 and discussed in Sect. 4. Section 5 presents the limitations of this investigation. Finally, Sect. 6 draws a conclusion and provides an outlook.

1.2 Contact and Channel Approach (C&C²-A)

The Contact and Channel Approach (C&C²-A) is a product modelling approach whose purpose is to support engineering designers in recognizing functionally relevant parameters of the embodiment. It is intended to be used during the embodiment design phase. For this purpose, the approach

provides elements and rules that are used to obtain a product model revealing the embodiment function relations of a technical system, starting from a preliminary representation of the embodiment. (Matthiesen 2002; Grauberger et al. 2020)

C&C²-A is based on three key modelling elements and three basic hypotheses that guide the application of these elements. "These [modelling elements] are the *Working Surface Pair* (WSP), *Channel and Support Structure* (CSS), and *Connector* (C):

- *Working Surface Pair* (WSP): Working Surface Pairs are surface elements. They are formed when two arbitrarily shaped surfaces of solid bodies or generalised interfaces of liquids, gases, or fields get into contact and are involved in the exchange of energy, substance, and / or information (Matthiesen 2002).
- *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. (Matthiesen 2002).
- *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 parameterised model of the relevant system environment; thus, they are within the observation area, but not within the design area (Alink 2010; Albers and Wintergerst 2014)." (Grauberger et al. 2020, p. 244).

The three basic hypotheses are as follows:

1. "Each element of a technical system that is relevant to its functions is involved in the fulfilment of functions by interactions with at least one other element. Interactions occur only in the case of contact between Working Surfaces (WSs), which together compose *Working Surface Pairs* (WSP) (Matthiesen 2002).
2. A function requires at least two *Working Surface Pairs* (WSP), which are connected by a *Channel and Support Structure* (CSS) and are both integrated by a *Connector* (C) into the environment. The properties, characteristics, and interactions of the WSPs, the CSSs, and the Connectors determine the functions (Albers and Wintergerst 2014).
3. Each subsystem can be described with *Working Surface Pairs* (WSP), *Channel and Support Structures* (CSS), and Connectors (C) at different levels of abstraction and detailing. For this purpose, a variation of the number, the

arrangement, and/or the properties of the illustrated key elements is required. (Albers and Wintergerst 2014)

With the key elements and basic hypotheses, the C&C²-Approach can be used for modelling.” (Grauberger et al. 2020, p. 245).

A variety of representations of the embodiment can be used as a starting point for modelling, for example, an initial hand sketch, a photo of a reference product, or a technical drawing. Therein, the key modelling elements are drawn onto the representation of the embodiment, so that in the end, the representation of the embodiment can be seen in the background and the modelling elements of the C&C²-A in the foreground. To guide engineering designers through the modelling process, Matthiesen et al. (2018) provide a seven-step modelling method: (1) Note the purpose of modelling; (2) set system boundary in space and time; (3) depict system in the fulfilment of functions; (4) track the flow of system variables; (5) display embodiment function elements in the system image; (6) identify functionally relevant design parameters; and (7) verify the model. The resulting product model is referred to as Contact and Channel Model (C&C²-M). An example is shown in Fig. 5.

1.3 Single Degree of Freedom (SDOF) system approach

A Single Degree of Freedom (SDOF) system approach¹ is a product modelling approach in which the technical system is described by a differential equation based on mass, stiffness, damping, and acting force. Therein, the position of the mass is described by a single coordinate at any given time. Its purpose is to analytically describe the behaviour of a technical system characterized by its motion due to an initial displacement or excitation. (Meirovitch 1986)

The basic form used in this investigation is a spring-damper-mass system with an acting force. This consists of a mass m , which is held in place by a spring with stiffness k and a damper with damping coefficient c , and is acted upon by a force $F(t)$. m , c , and k are the system parameters and are assumed to be constant. The position of the mass is described with the displacement $x(t)$. The motion of the mass can be described by the second-order differential equation given in Eq. 1. (Meirovitch 1986) Regarding the mathematical solution of the differential equation, we would like to refer you to standard works such as Hartog (1985), Meirovitch (1986), or Rao (2004).

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \quad (1)$$

When modelling technical systems as SDOF systems, they are converted into the descriptive equation of motion and, if necessary, the values of the system parameters are determined. This can be done by first graphically representing the technical system as a substitute system consisting of mass, spring(s), and damper(s), which can then be easily converted into the equation through an equilibrium of forces. Examples of technical systems that can be represented well in this way are a piston that moves exclusively in a linear motion in a cylinder and a crankshaft that rotates in a rigid bearing (Hartog 1985). If the technical system to be modelled possesses multiple degrees of freedom, it can still be simplified into an SDOF system, which then, however, only models the behaviour of the technical system to a limited extent. In this case, multiple masses, stiffnesses, or dampers are combined and the number of degrees of freedom is reduced. An example of such a built SDOF system is shown in Fig. 6.

2 Materials and methods

An overview of the procedure for investigating the possibility of linking the C&C²-A and SDOF system approach is shown in Fig. 1. First, it is investigated whether a linking possibility between the two product modelling approaches can be identified. The existing method by Paehler et al. (2025) is used for this purpose. Within this method, a design problem is defined in which the investigation is carried out. In this publication, the vibration behaviour of an angle grinder is used as the design problem. The method and the design problem are described in more detail in Sect. 2.1. From this, it can be determined whether or not a linking possibility has been identified. In addition, it provides model-based insights into the vibration behaviour of the angle grinder for the design problem used. Since the accuracy of the model-based insights is crucial for the potential benefits of the linked product modelling approaches in design practice, these insights are then evaluated. To this end, the model-based insights are compared with findings that are already available in the literature from an experimental investigation on a test bench. The findings obtained experimentally by Sturm et al. (2022) are used to this end. The evaluation of the accuracy used for this purpose is presented in Sect. 2.2.

¹ To differentiate between the product modeling approach and the resulting product model, this publication always uses SDOF system approach when referring to the product modeling approach. In contrast, SDOF system refers to the resulting product model.

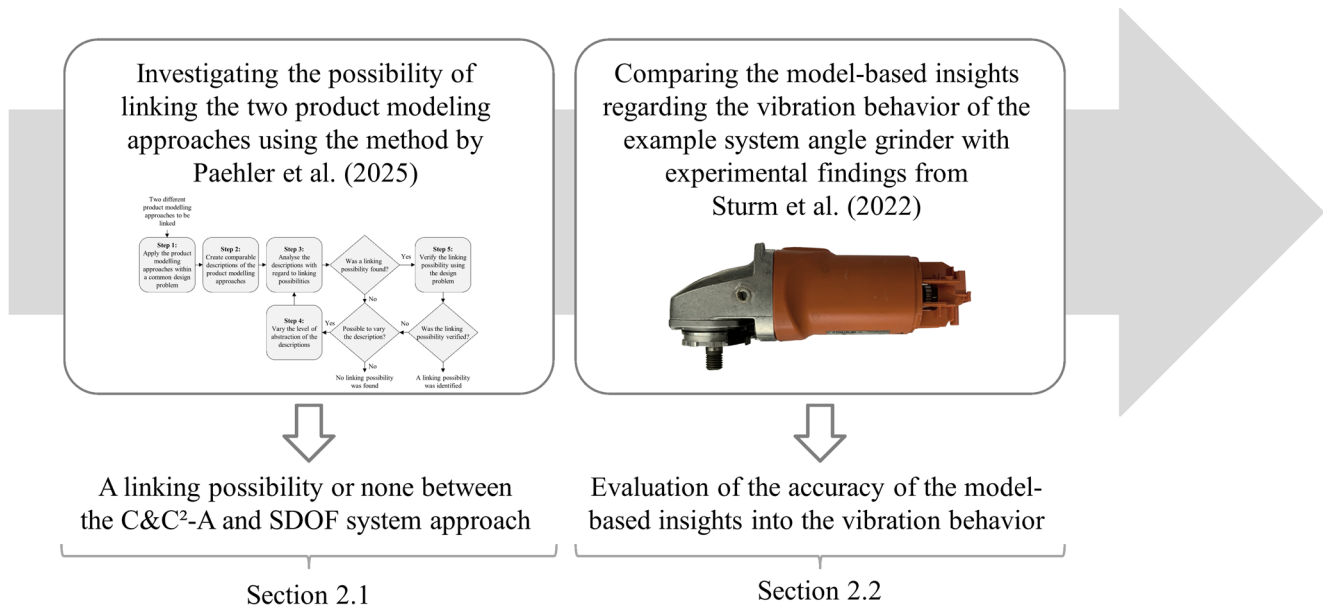


Fig. 1 An overview of the investigation procedure concerning the linking possibility between the C&C²-A and the SDOF system approach

2.1 Identifying a linking possibility between the C&C²-A and SDOF system approach

The used method provided by Paehler et al. (2025) aims to enable researchers to identify new linking possibilities between product modelling approaches in engineering design research. The method involves five steps that are iterated until either a linking possibility is found or a break-off criterion is reached, meaning that no linking possibility could be found. It is based on obtaining comparable textual descriptions of the two product modelling approaches in the context of a common design problem, and identifying a link within these descriptions, which is then verified subsequently. The method's steps and their sequence are shown in Fig. 2 and their application within this investigation is described below. The whole description of the method in this subsection is based on Paehler et al. (2025) and is not marked separately for readability.

In **Step 1**, the C&C²-A and SDOF system approach are applied within the context of a common, hypothetical design problem. Both product modelling approaches must contribute to solving the problem. In this investigation, a design problem is used based on the example system of an angle grinder. The design problem is as follows: *During the development of a new generation of an angle grinder, a requirement is that the radial amplitude of displacement as part of the vibration behaviour of the drive shaft must be reduced compared to the previous generation. Therefore, design changes to reduce the amplitude of displacement must be derived. However, it is unknown which design changes can reduce the amplitude of displacement.* This problem is suitable for the intended linking, as a sole consideration of the

embodiment function relations with the C&C²-A does not include considerations about the vibration behaviour, while the SDOF system approach does not include considerations about possible design changes.

A Fein WSG 11–125 angle grinder is considered as previous generation and used as starting point for modelling, since this was also investigated by Sturm et al. (2022) (see Sect. 2.2). The manufacturer's part numbering is used to achieve a common nomenclature for the parts, assemblies etc. of the angle grinder during modelling. Part numbers are indicated by "PT-" in the text and figures. The angle grinder, including the main components and part numbering, is shown in Fig. 3. The C&C²-M for the design problem is built according to Matthiesen (2021) and the SDOF system according to Hartog (1985). These are built by one of the authors and then reviewed in workshops with the other authors. In this workshop, the following review criteria are applied: formal correctness of the modelling process based on its documentation, formal correctness of the presented models, and the traceability of the conclusions drawn from the models. In the event of conflicting opinions, a consensus is pursued through discussion. The reviewers do not have knowledge of the experimental findings of the investigation by Sturm et al. (2022) (see Sect. 2.2), which could influence the review. Thereby, at the end of this step, the two product models built with the respective two product modelling approaches are available.

In **Step 2**, both product modelling approaches are described in a standardized way based on their application in Step 1. For this purpose, the proposed template for describing product modelling approaches in engineering

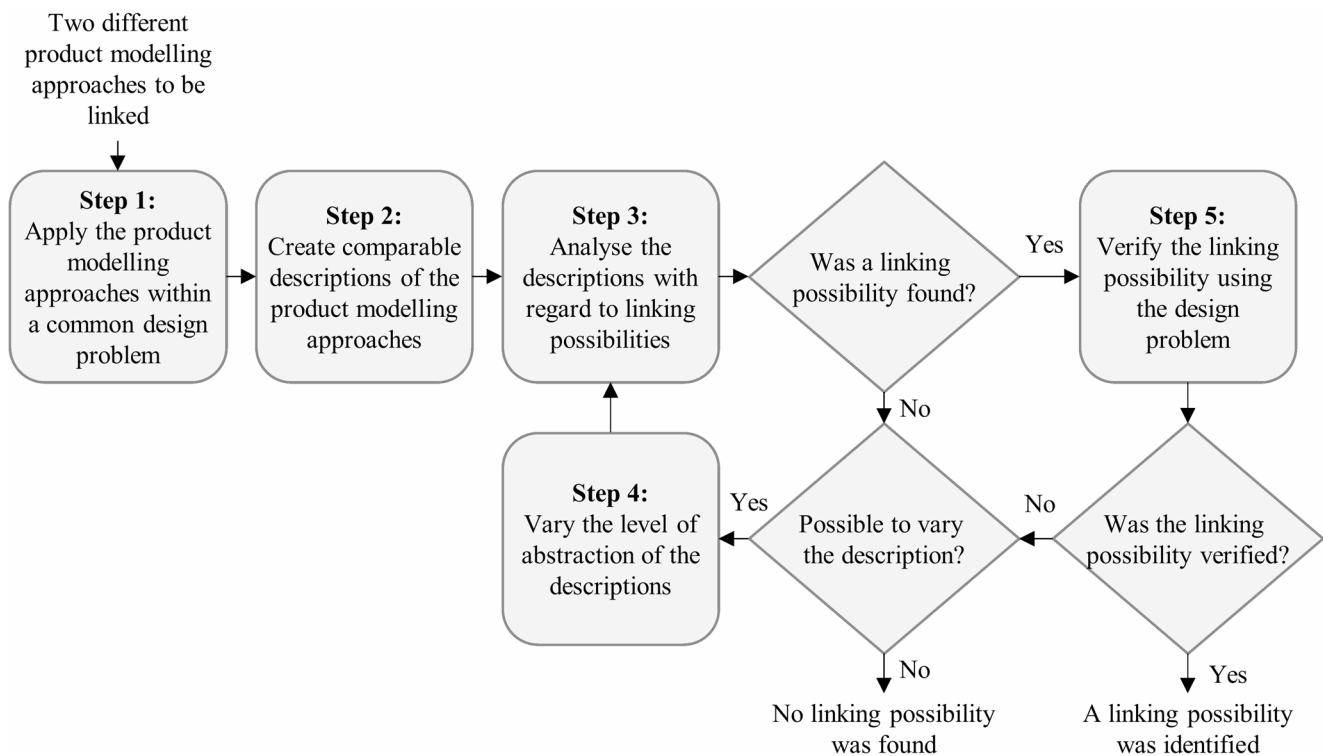
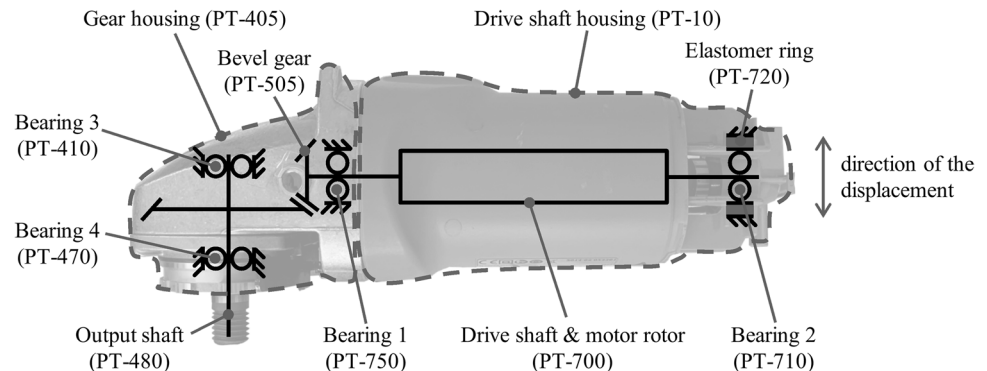


Fig. 2 The method used to investigate the possibility of linking the C&C²-A and SDOF system approach (adapted from Paehler et al. 2025)

Fig. 3 The technical system considered in the context of the design problem, a Fein WSG 11–125 angle grinder (based on C. & E. Fein Service GmbH; Sturm et al. 2022)



design research according to Paehler et al. (2026)² is used. It defines three different objectives for describing product modelling approaches: usage, representation, and functionality. The template is shown in Table 1. However, only the representation and functionality are relevant for linking product modelling approaches. Accordingly, the two product modelling approaches are described in as much detail as possible in terms of their representation and functionality in this step. The two resulting textual descriptions of the C&C²-A and SDOF system approach are the outcome.

In **Step 3**, the descriptions of the product modelling approaches from Step 2 are analysed with regard to linking

possibilities. The following two questions are considered for this purpose:

1. Is there an overlap between the data/information/knowledge resulting from one product modelling approach that can be incorporated into the other product modelling approach? To answer this question, the “modelled attributes” and the “output” of one product modelling approach are compared with the “input” and “manipulating” of the other product modelling approach and vice versa. An overlap must occur in only one of the comparisons for the question to be answered with yes and, in this case, question b) follows.
2. Is there an overlap between the representation of the data/information/ knowledge between the two

² While Paehler et al. (2025) referred to the preprint version of the template, the final published version of the template is referred to here.

Table 1 The template for describing product modelling approaches in engineering design research(adapted from Paehler et al. 2026)

Objective of the description	Aspects to consider and their leading question	
The usage of the product modelling approach	Purpose	What is the resulting product model used or intended to be used for?
	Stage/phase of design	When is the resulting product model used or intended to be used within a design process?
	Requirements	What limitations need to be considered when using the resulting product model in a design process?
The representation of the product modelling approach	Modelled attributes	What attributes of the technical system (e.g., geometry, function, etc.) are represented in the resulting product model?
	Modelling language	How is the content of the resulting product model represented?
	Principle	What is the foundation (e.g., paradigm, theory, principle, etc.) on which the product modelling approach is based?
The functionality of the product modelling approach	Integration	How is the resulting product model technically integrated into a design process?
	Input	Which data, information, knowledge, or other product model is used as the basis for building the product model?
	Creating	How is the product model build?
	Manipulating	How can the resulting product model be modified?
	Output	What data, information, or knowledge can the resulting product model provide?
	Succeeding model	Which other product model(s) can be built from the resulting product model?

product modelling approaches? To answer this question the “modelling language” between the two product modelling approaches are to be compared. They must be in agreement to answer the question with yes.

If the answer to question 1) is “no”, there is no linking possibility. If the answer to question (1) is “yes”, a linking possibility has been identified. Question (2) then serves to classify whether the data/information/knowledge is available in the same type of representation (“yes”) or whether the data/information/knowledge still needs to be processed when using the link (“no”).

If no linking possibility is found in Step 3 and the textual descriptions from Step 2 are specific enough to be abstracted further, Step 4 follows. In **Step 4**, the textual descriptions are taken and the level of abstraction of the individual aspects of the product modelling approaches described is increased. For example, if the modelling language was described using model-specific terms from the C&C²-A, it is now attempted to use a more commonly used term instead. This results in additional textual descriptions of the two product modelling approaches more abstract than before, which are analysed in Step 3 in addition to the descriptions that were already available from Step 2 previously.

If a linking possibility is identified in Step 3, Step 5 follows. In **Step 5**, the identified linking possibility is verified in the context of the design problem. This means that the two product modelling approaches are used again to build the product models for solving the design problem. In contrast to Step 1, however, these are not applied independently of each other. Instead, the product modelling approach that provides data/information/knowledge is applied first. Subsequently, the second product modelling approach is applied, attempting to incorporate the data/information/

knowledge as described by the identified link. If this can be successfully incorporated into the second product modelling approach, the linking possibility between the product modelling approaches is assumed to work. With respect to the design problem, if the linking possibility is verified, model-based insights are gained, i.e., design changes that are intended to lead to a reduction in the amplitude of displacement of the drive shaft.

2.2 Comparing the insights regarding vibration behaviour with experimental findings from the literature

In order to evaluate the accuracy of the model-based insights into possible design changes that are intended to reduce the amplitude of displacement as part of the vibration behaviour of the drive shaft, these are compared with the experimental findings of Sturm et al. (2022).

Sturm et al. (2022) investigated the targeted influencing of vibrations in drive trains on the Fein WSG 11–125, which is also used during the modelling described in Sect. 2.1. The intent was to deliberately influence the radial vibrations of the drive shaft by adjusting design parameters of the bearing seat of bearing 2. To this end, FE models were first used to investigate the influence of the bearing seat design (consisting of rib height, rib thickness, and bearing seat spacing) on the bearing seat stiffness. The preliminary findings were then used to design and manufacture a new bearing seat design. This was then tested on a drive train test bench at a constant speed of 10,000 rpm in comparison to the previous bearing seat design. Figure 4 shows the measured amplitudes of displacement of the drive shaft for both the previous and new bearing seat designs, including the acceleration and deceleration phases on the test bench. It shows a substantial

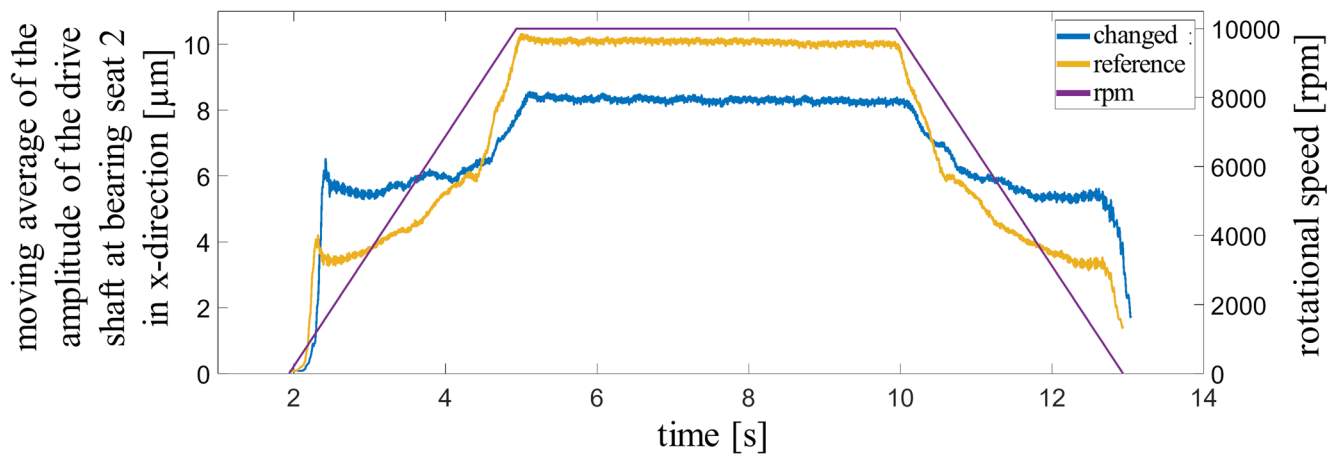


Fig. 4 Comparison of the drive shaft's amplitude of displacement between the previous bearing seat design ("reference") and the new bearing seat design ("changed") (adapted from Sturm et al. 2022)

reduction in the amplitude of displacement of the drive shaft in the centre at constant speed. Thereby, the investigation showed that an increase in rib height and thickness, as well as a reduction in bearing seat spacing, led to an increase in radial bearing seat stiffness. The increase in radial bearing seat stiffness in turn led to a reduction in the amplitude of displacement of the drive shaft. (Sturm et al. 2022)

The experimentally obtained findings from Sturm et al. (2022) thus provide a suitable basis for evaluating the accuracy of the qualitative model-based insights into design changes in terms of their direction.

3 Results

Analogous to Sect. 2, the results from identifying the linking possibility between C&C²-A and the SDOF system approach are presented first, followed by the comparison of the model-based insights with the experimental findings.

3.1 The identified linking possibility between the C&C²-A and SDOF system approach

In the following, the preliminary results of the steps of the method are presented before the final result in the form of the identified linking possibility is presented.

The product models built within the context of a common design problem in **Step 1**, the C&C²-M and SDOF system, are shown in Figs. 5 and 6.

The C&C²-M (Fig. 5) was built according to Matthiesen (2021). Therein, the purpose of modelling was defined as "identifying characteristics and properties of the angle grinder's embodiment that can influence the amplitude of displacement of the drive shaft." This resulted in the C&C²-M shown, consisting of the three basic elements

depicted in green within the embodiment, as well as the labelling with the basic elements' properties and characteristics. The labels of the basic elements follow the common nomenclature, based on the manufacturer's part numbering. Properties or characteristics that are expected to influence the amplitude are shown in bold.

The SDOF system (Fig. 6) was modelled according to Hartog (1985). Therein, the drive shaft (PT-700), including the bevel gear (PT-505) fitted to it, was assumed to be the vibrating mass. The combination of the components involved in the bearing seats were modelled as springs and damper. This resulted in the equation of motion as a function of the masses, stiffnesses, and damping of the parts, as well as the force acting on the bevel gear, as given in Eq. 2.

$$(m_{PT-505} + m_{PT-700})\ddot{x} + c_{PT-720}\dot{x} + (k_1 + k_2)x = F(t) \quad (2)$$

To solve the equation of motion, the excitation $F(t)$ is considered first. It results from the meshing of the two bevel gears, which have a tooth overlap factor of 2. Given the stationary operating point shown in Fig. 4 ("reference") at a rotational speed of 10,000 rpm and a constant amplitude of displacement at around 10 μm , the excitation $F(t)$ can be regarded as a superposition of a constant mean and a dynamic component (see Eq. 3). The dynamic component is assumed to be a sine function.

$$F(t) = F_{mean} + F_{dyn} \sim F_0 + F_A \sin(\Omega t) \quad (3)$$

Based on Eq. 3, it is assumed that the displacement x can also be modelled as a sine function as shown in Eq. 4 (cf. Hartog 1985). The constant and dynamic component of this equation can now be considered separately. These represent a static displacement and a superimposed vibration.

Fig. 5 The C&C²-M of the angle grinder built to identify characteristics and properties influencing the amplitude of displacement of the drive shaft

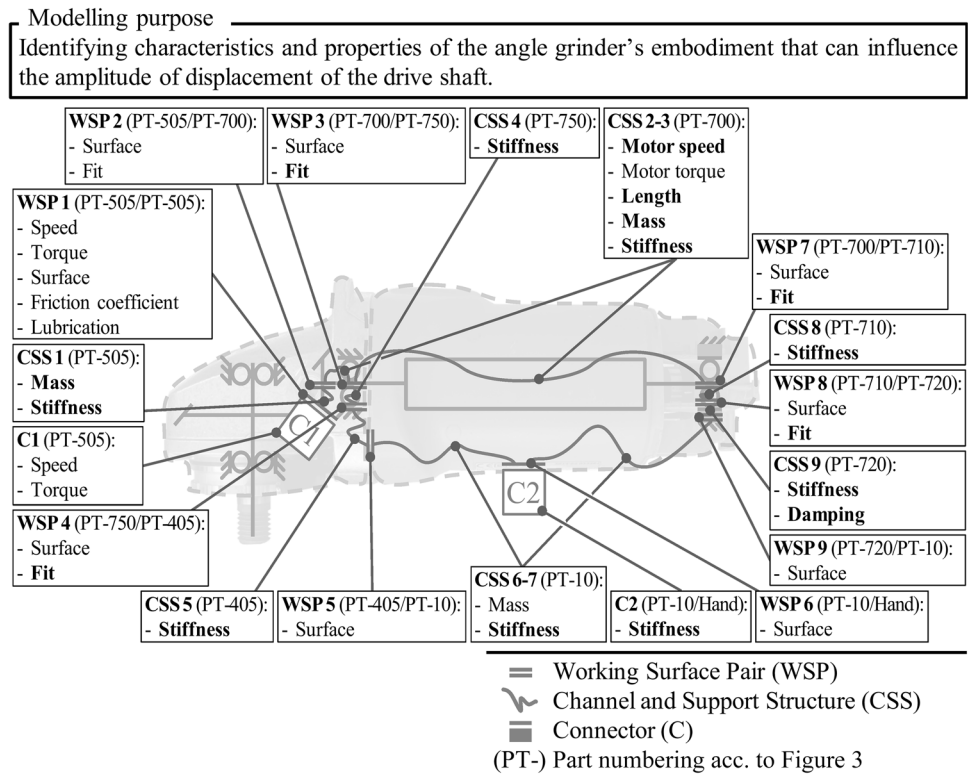
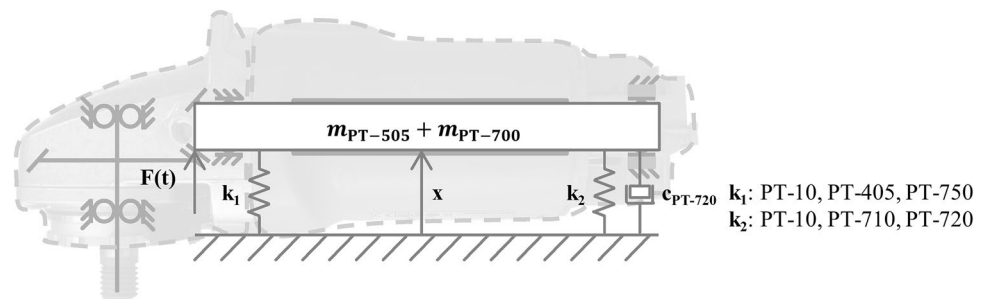


Fig. 6 The SDOF system built for modelling the amplitude of displacement of the drive shaft of the angle grinder



$$x(t) = x_0 + x_A \sin(\omega t - \varphi) \quad (4)$$

When considering the constant component, $\dot{x}=0$, $\ddot{x}=0$, and $F_A=0$ applies, as this is a stationary operating point with constant displacement. Substituting this into Eq. 2 and rearranging the equation in terms of x_0 results in Eq. 5. Equation 5 shows that the component x_0 decreases when the stiffnesses k_1 and k_2 are increased. Mass and damping have no influence on x_0 .

$$x_0 = \frac{F_0}{k_1 + k_2} \quad (5)$$

Applying mass, stiffness and damping as given in Eq. 2, Eq. 6 and Eq. 7 based on Hartog (1985) can be used to consider the dynamic component. According to Eq. 6, x_A is influenced by the mass, stiffness and damping, which therefore also influence the dynamic component. However, given

the considered stationary operating point (see Fig. 4, “reference”), it is clear that the constant component dominates the “global” amplitude of displacement. The dynamic component is therefore negligible when considering the amplitude of displacement.

$$x_A = \frac{F_A}{\sqrt{(c_{PT-720}\omega)^2 + (k_1 + k_2 - (m_{PT-505} + m_{PT-700})\omega^2)^2}} \quad (6)$$

$$\tan(\varphi) = \frac{c_{PT-720}\omega}{k_1 + k_2 - (m_{PT-505} + m_{PT-700})\omega^2} \quad (7)$$

The SDOF system thus indicates that, in order to reduce the amplitude of displacement, the stiffnesses k_1 and k_2 should be increased. The masses m_{PT-505} and m_{PT-700} , as well as the damping c_{PT-720} , can be considered secondary regarding the amplitude of displacement under the given operating conditions.

Table 2 Textual description of the C&C²-A regarding its representation and functionality (Step 2) and identified linking possibility (underlined) (Step 3)

Described aspects	Description of the C&C ² -A
The representation of the product modelling approach	
Modelled attributes	Contact surfaces and the force-transmitting embodiment, including their properties and characteristics (stiffness, mass, length, surface, fit, damping, torque, and speed) (PT-10, PT-405, PT-505, PT-700, PT-710, PT-720, PT-750) within the system boundaries, as well as the connection to the environment (PT-505, Hand)
Modelling language	Graphical (working surface pairs, channel and support structures, and connectors); textual (properties & characteristics)
Principle	Three key modelling elements that are applied on the basis of three basic hypotheses in order to abstract the relationship between embodiment and function
The functionality of the product modelling approach	
Integration	None
Input	A photo and a schematic sketch of an angle grinder (Fein Compact Angle Grinder WSG 11–125)
Creating	1) Note the purpose of modelling: Identifying characteristics and properties of the angle grinder's embodiment that can influence the amplitude of the drive shaft; 2) Define the system boundaries: The drive shaft (PT-700) including its connection to the hand and to the engaged gear (PT-505); 3) Depict the system during function fulfilment; 4) Track the flow of system variables; 5) Display embodiment function elements in the system depiction; 6) Identify function-relevant embodiment parameters (and formulate the connection to the fulfilled function) 7) The step “verify the model” of the modelling method is omitted, as it would involve an experimental investigation that would interfere with the intended subsequent comparison with experimental findings from Sturm et al. (2022).
Manipulating	By changing the model elements (WSP, CSS, or C's) or their characteristics and properties (stiffness, mass, length, surface, fit, damping, torque, and speed)
Output	With regard to the design problem, the following properties/characteristics can influence the amplitude of displacement of the drive shaft: fit of WSP 3 (PT-700/PT-750), stiffness of CSS 4 (PT-750), motor speed, length, mass, and stiffness of CSS 2–3 (PT-700), fit of WSP 7 (PT-700/PT-710), stiffness of CSS 8 (PT-710), fit of WSP 8 (PT-710/PT-720), stiffness and damping of CSS 9 (PT-720), stiffness of CSS 6–7 (PT-10), stiffness of CSS 5 (PT-405), fit of WSP 4 (PT-750/PT-405), mass and stiffness of CSS 1 (PT-505).
Succeeding model	None

In **Step 2**, the product modelling approaches were described focusing on their representation and functionality according to the template. The description of the C&C²-A is shown in Table 2, and the description of the SDOF system approach is shown in Table 3. These include both the representation and the functionality, and are described in as much detail as possible. The input is identical in both descriptions due to the method used: In both cases, the input consists of the photo and a schematic sketch of the angle grinder, as shown in Fig. 3.

The textual descriptions of the two product modelling approaches were subsequently analysed in **Step 3** with regard to linking possibilities. The consideration of a possible flow of data/information/knowledge from C&C²-A

to SDOF system approach revealed no match and, accordingly, no linking possibility. However, the analysis from SDOF system approach to C&C²-A resulted in a match. Therein, an overlap between the output of the SDOF system approach and manipulating the C&C²-A emerges: The SDOF system approach provides the information that k_1 (PT-10, PT-405, PT-750) and k_2 (PT-10, PT-710, PT-720) have to be increased to reduce the amplitude of displacement while m_{PT-505} , m_{PT-700} , and c_{PT-720} can be neglected, which can be included in the C&C²-A in terms of the properties of the respective model elements (CSS4 (PT-750), CSS 2–3 (PT-700), CSS 8 (PT-710), CSS 9 (PT-720), CSS 6–7 (PT-10), CSS 5 (PT-405), and CSS 1 (PT-505)). That is, k and stiffness, m and mass, and c and damping overlap. In

Table 3 Textual description of the SDOF system approach regarding its representation and functionality (Step 2) and identified linking possibility (underlined) (Step 3)

Described aspects	Description of the SDOF system approach
The representation of the product modelling approach	
Modelled attributes	Amplitude of displacement as part of the vibration behaviour of the drive shaft including the bevel gear (PT-505, PT-700) as a function of the stiffness (PT-10, PT-405, PT-710, PT-720, PT-750) and damping properties (PT-720) of the drive shaft bearing and the force acting on the bevel gear (PT-505)
Modelling language	Analytically as an equation of motion
Principle	Equation of motion for mechanical vibrations from technical mechanics
The functionality of the product modelling approach	
Integration	None
Input	A photo and a schematic sketch of an angle grinder (Fein Compact Angle Grinder WSG 11–125)
Creating	1) Building a substitute model consisting of a concentrated mass, springs, and dampers. This includes the drive shaft including bevel gear (PT-700, PT-505), two springs (PT-10, PT-405, PT-710, PT-720, PT-750) and a damping element (PT-720) of the drive shaft bearing, and the force acting on the gear wheel (PT-505); 2) Formulation of the corresponding equation of motion as a function of mass (PT-700, PT-505), stiffness (PT-10, PT-405, PT-710, PT-720, PT-750), damping (PT-720), and the force acting on the gear (PT-505); 3) Rearrangement of the equation of motion and related equations in terms of amplitude of displacement x
Manipulating	By changing the mass (PT-700, PT-505), stiffness (PT-10, PT-405, PT-710, PT-720, PT-750), or damping (PT-720), as well as the acting force (PT-505)
Output	A reduction in the amplitude of displacement of the drive shaft (PT-700) including the bevel gear (PT-505), can be achieved by increasing k_1 (PT-10, PT-405, PT-750) and k_2 (PT-10, PT-710, PT-720), while m_{PT-505} , m_{PT-700} , and c_{PT-720} have a negligible influence regarding the amplitude of displacement.
Succeeding model	None

contrast, the comparison of the representations of the data/information/knowledge between the two product modelling approaches revealed no overlap. Thus, a linking possibility was identified, where the data/information/knowledge still needs to be processed.

To specify, the linking possibility between the product modelling approaches is that the SDOF system approach provides the direction of change in the properties of parts or which properties to neglect as output so as to influence the amplitude of displacement as part of the vibration behaviour. The C&C²-A integrates the provided direction of change or neglect of the properties into the properties of the model elements to manipulate the product model, thereby integrating the provided changes into the embodiment function relations.

As a linking possibility has been identified, **Step 4** is to be omitted according to the used approach (see Fig. 2), and Step 5 follows.

In **Step 5**, the intent was to use the identified link and transfer the output of the SDOF system approach to the manipulation of the C&C²-A. Since the already built SDOF system from Step 1 is not affected by the linking possibility,

the SDOF system shown in Fig. 6 is still applicable. This provides the following output, as stated in Table 3: “A reduction in the amplitude of displacement of the drive shaft (PT-700), including the bevel gear (PT-505), can be achieved by increasing k_1 (PT-10, PT-405, PT-750) and k_2 (PT-10, PT-710, PT-720), while m_{PT-505} , m_{PT-700} , and c_{PT-720} have a negligible influence regarding the amplitude of displacement.” Since this output is to be integrated into the manipulation of the C&C²-A, the initially built C&C²-M from Step 1 (see Fig. 5) can be adopted.

As determined in Step 3, the data/information/knowledge must be processed for the linking possibility to be used. The information provided by the SDOF system approach is therefore transferred to the model elements of the C&C²-A as follows: Increasing k_1 (PT-10, PT-405, PT-750) and k_2 (PT-10, PT-710, PT-720) relates to an increase of the stiffness of CSS 6–7 (PT-10), CSS 5 (PT-405), CSS 8 (PT-710), CSS 9 (PT-720), and CSS 4 (PT-750); neglecting m_{PT-505} and m_{PT-700} relates to an maintaining of the mass of CSS 1 (PT-505) and CSS 2–3 (PT-700); and neglecting c_{PT-720} relates to maintaining the damping of CSS 9 (PT-720). Accordingly, the information provided results in corresponding

Fig. 7 The updated C&C²-M of the angle grinder, which, due to the linking with the SDOF system, now indicates the direction of how design parameters need to be changed to achieve a targeted change in amplitude of displacement as part of the vibration behaviour of the drive shaft as well as properties that can be maintained

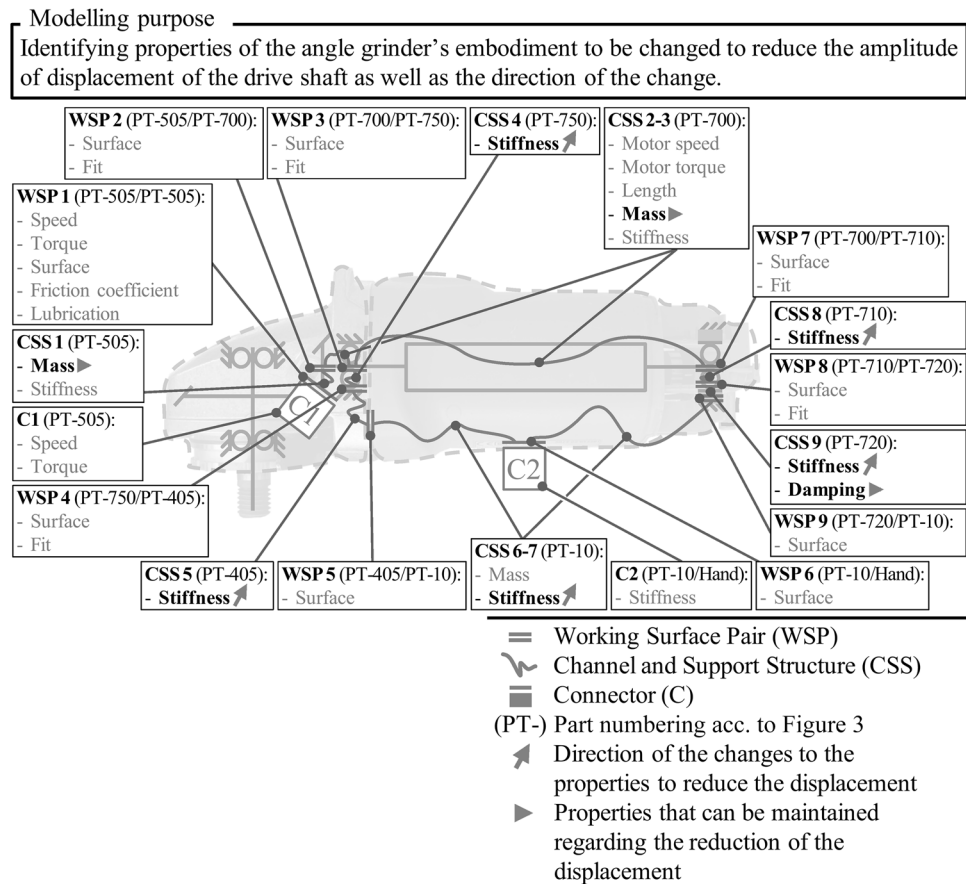


Table 4 Comparison of model-based insights and experimental findings regarding the reduction of the amplitude of displacement as part of the vibration behaviour

Model-based insights of possible design changes to reduce the amplitude of displacement	Experimentally obtained findings from Sturm et al. (2022) to reduce the amplitude of displacement
The mass of the bevel gear (PT-505) can be maintained	An increase in bearing seat stiffness led to a reduction in the amplitude of displacement of the drive shaft (see Fig. 4).
The mass of the drive shaft (PT-700) can be maintained	
Increase the stiffness of bearing 1 (PT-750)	
Increase the stiffness of the gear housing (PT-405) surrounding bearing 1	
Increase the stiffness of bearing 2 (PT-710)	
Increase the stiffness of the drive shaft housing (PT-10) surrounding bearing 2	
Increase the stiffness of the elastomer ring (PT-720) as part of bearing 2's bearing seat	
The damping of the elastomer ring (PT-720) as part of bearing 2's bearing seat can be maintained	

manipulations to the properties of the model elements of the C&C²-A.

While several characteristics and properties were initially identified in the C&C²-M, as shown in Fig. 5, which were expected to influence the amplitude, the information provided by the SDOF system results in fewer properties to be changed and the direction of the changes to reduce the amplitude of displacement as well as properties that can be maintained. Figure 7 shows the updated C&C²-M, in which the changes to be made to the properties are indicated by red

arrows. Properties which can be maintained are indicated by a red triangle. Since the integration of the information was achieved, the verification of the linking possibility between the product modelling approaches within the design problem was successful. The changes to the properties also indicate which design changes need to be made in order to reduce the amplitude of displacement as part of the vibration behaviour of the drive shaft, and thereby provide model-based insights as a solution to the design problem.

3.2 The comparison of the model-based insights regarding vibration behaviour with experimental findings from the literature

To compare the model-based insights with the experimental findings, they are presented side by side in Table 4. The part numbering and model elements used in the C&C²-M were traced back to the parts of the angle grinder using Fig. 3, so that their relations within the system become clear. Table 4 shows that, with regard to the model-based insights on maintaining mass and damping, there are no experimental findings from Sturm et al. (2022) available for comparison. With regard to stiffness, the model-based insights indicate that an increase in the stiffness of the bearings and their bearing seats leads to a reduction in the amplitude of displacement of the drive shaft. The increase in bearing seat stiffness is in line with the experimental findings. The change in bearing stiffness is not covered in the experimental findings, but is logically in line with the bearing seat stiffness. Hence, the evaluation shows that the model-based insights regarding stiffness are qualitatively in line with the experimental findings, but that the insights regarding mass and damping can not be evaluated based on the experimental findings by Sturm et al. (2022).

4 Discussion

The research question “How can a link between C&C²-A and SDOF system approach be established so that the insights regarding vibration behaviour can be incorporated into qualitative embodiment function relations modelling?” is answered through the identified linking possibility: The SDOF system approach provides how the properties of the technical system are to be changed to achieve a targeted change in the vibration behaviour, while the C&C²-A integrates these changes into the modelled embodiment function relations to support design decisions on this basis. In the context of the design problem under consideration, using the angle grinder as an example system, this linking possibility has led to possible design changes in order to achieve the desired reduction in the amplitude of displacement as part of the vibration behaviour of the drive shaft. The design changes for which experimental findings from the literature are available for comparison proved to be accurate. For the remaining model-based insights, no experimental findings are yet available, so they should be evaluated in future experiments. Thus, the desired link between the qualitative product modelling approach focused on embodiment function relations and the product modelling approach considering the vibration behaviour has been successfully established.

The capabilities provided by the linking possibility between the two product modelling approaches differ from those discussed in the introduction as part of the current state of research. In comparison to the established product modelling approaches for considering the vibration behaviour, such as the MDOF system approach, MBS and FEM, the linked product modelling approaches require less available information, for example regarding material behaviour and damping properties. This is mainly because no parameterisation takes place during modelling. However, this also results in the limitation that only model-based insights on relative changes in qualitative vibration behaviour can be obtained and no absolute values. It is therefore not possible to check whether a defined threshold value for vibration behaviour is being met. In addition, the technical system has been simplified more by considering it as a SDOF system in comparison to a MDOF system or FEM analysis. Interactions between vibrations in the technical system and different spatial directions have therein been neglected. In contrast to qualitative product modelling approaches focused on embodiment function relations, the linked product modelling approaches can not only identify design parameters that may influence vibration behaviour, but also indicate the direction of how these design parameters need to be changed. This is evident when comparing the progress from Figs. 5, 6 and 7. Thus, the linked product modelling approaches are more capable together than the previous individual product modelling approaches in terms of an early applicable consideration of vibration behaviour. Therein, the linked product modelling approaches are particularly suitable for an initial consideration.

In order for the linked product modelling approaches to be applicable for an initial consideration, both the prerequisites for the two individual product modelling approaches as well as for the identified link must be met. As such, a necessary step in the C&C²-A is to trace the flow of system variables, typically force. Technical systems whose function arises from hydraulic or pneumatic flows, or which involve complex electromagnetic interactions, result in modelling problems and should therefore be avoided. To ensure that a technical system can be simplified and modelled meaningfully as an SDOF system, the following prerequisite must be met: there must be a dominant vibration in one spatial direction, which must be only weakly coupled to vibrations in other spatial directions, and it must be possible to concentrate the masses, stiffnesses and damping factors into discrete elements in a meaningful way. For the link, it is crucial that there is an overlap between the modelled properties of the technical system in both product modelling approaches. Only then can insights into the properties be transferred from the SDOF system approach to the C&C²-A. Thus,

these prerequisites must be assessed before using the linked product modelling approaches to support design decisions.

While the linked product modelling approaches can support design decisions, the decision itself must still be made by the engineering designer. In some cases, there are several ways to implement the model-based insights into design changes. In the considered design problem, if we consider the insight into increasing the housing stiffness at bearing 2 (Table 4: “Increase the stiffness of the drive shaft housing (PT-10) surrounding bearing 2”), there are several ways to change this stiffness. For example, the embodiment could be maintained and a different material with different material properties could be used instead, the housing thickness around the bearing could be increased, or additional ribs could be added to reinforce the bearing seat. In another example, the stiffness of bearing 2 (Table 4: “Increase the stiffness of bearing 2 (PT-710)”) could be increased by switching from a ball bearing to a cylindrical roller bearing. In each of these examples, a transition from a property which can not be influenced directly by the designer to an adjustable characteristic is made (see Weber 2014). This transition and how these design decisions ultimately behave in the technical system are to be assessed by the engineering designer, potentially at a later stage in the product development process through appropriate quantitative modelling and experimental testing.

Based on the discussed prerequisites and possibilities of the linked product modelling approaches, two key ways in which the linked product modelling approaches can be integrated into design practice can be outlined. On the one hand, a design method based on the link could be developed. This method would be a thinking tool for engineering designers, supporting them during initial considerations of the influence of design changes on vibration behaviour or guiding them in making design changes to achieve a desired change in vibration behaviour. Using this design method, design decisions could be derived and evaluated in the further course of the product development process. Another possibility would be to develop the link into an analysis method for narrowing down the parameter space prior to quantitative modelling and simulation, e.g. with MBS or FEM. Through the link, an analysis of the technical system could be carried out to identify promising parameters that should be considered in a subsequent simulation of vibration behaviour. The aim would be to reduce the amount of parameters to consider in the simulation. Thus, by further investigating the link in the future and developing methods based on it, it could be incorporated into design practice.

Through the identification of the link between the C&C²-A and the SDOF system approach, further more general methodological insights for identifying linking possibilities can be derived. As such, the applied methodology for

identifying the link has, in particular, led to traceable steps and interim results. Therein, the value of the application of the two product modelling approaches for the same design problem is evident. This key step of the methodology could therefore also be utilised in the future when identifying linking possibilities. At the same time, this step also results in the need for further substantial investigations, since generalisability can not be guaranteed (see Sects. 5 and 6). In this context, the choice of design problem is therefore of great importance in terms of identifying the link and the applicability of the linked product modelling approaches. Examining generalisability is, therefore, an essential next step towards ensuring the intended support for design practice through the linked product modelling approaches.

5 Limitations

The investigation of the linking possibility between the C&C²-A and SDOF system approaches was closely linked to the design problem based on the angle grinder example system. This results in several limitations, particularly with regard to transferability:

- The applicability of the linking possibility has so far only been demonstrated for the design problem involving the angle grinder. Although the angle grinder is well suited for this study due to its complicated vibration behaviour, it was simplified and the findings are limited in their transferability. It is not yet possible to say to what extent the linking possibility encounter limitations in terms of their applicability in other technical systems or design problems. Such a limitation could be reached, for example, if the technical system can not be feasibly simplified to an SDOF system or if the simplification would mean that the insights gained could no longer be applied to the technical system.
- The accuracy of the insights derived from the linking possibility has also only been evaluated in the case of the design problem involving the angle grinder and still requires further experiments as some experimental findings are missing. It is therefore not possible to determine from this study in which cases of other technical systems and design problems the insights will be correct and in which cases they will be incorrect. As even multiple further investigations would not eliminate the risk of an incorrect insight, it will always remain the responsibility of engineering designers to critically assess the model-based insights and to verify them through experimental testing.

6 Conclusion and outlook

This investigation was motivated by the fact that existing product modelling approaches for early embodiment design fall short in terms of considering the vibration behaviour of technical systems. By identifying a linking possibility between two existing qualitative product modelling approaches, the C&C²-A and SDOF system approach, it was possible to show how vibration behaviour can be considered in the context of a design problem of an angle grinder. Therein, the SDOF system approach provided the consideration of vibration behaviour, which was integrated into the embodiment function relations of the C&C²-A. On this basis, design changes could be derived for influencing the vibration behaviour in a targeted way. An assessment of vibration behaviour in absolute values was not possible. In conclusion, linking these product modelling approaches represents a first step in the direction of an early consideration of vibration behaviour in embodiment design to support informed design decisions.

The outlined results and limitations lead to the following outlook for future research:

- The accuracy of model-based insights obtained through the linked product modelling approaches should be further investigated. On the one hand, the already derived model-based insights concerning the design problem of the angle grinder, for which no experimental findings were yet available in the literature, should be evaluated through appropriate experiments. On the other hand, other design problems and technical systems should be examined using the linked product modelling approaches to assess the accuracy of the model-based insights in these cases or identify limitations.
- The applicability of the linked product modelling approaches for engineering designers should be thoroughly investigated. To this end, the linking possibility must be implemented in an applicable product modelling approach or design method that can be passed on to and applied by engineering designers. This would lay the foundation for investigating the applicability in terms of modellable technical systems, design problems under consideration, and for the ease of use for engineering designers themselves as users.
- The established link can also be regarded as proof of concept for linking a product modelling approach with a focus on embodiment function relations and a product modelling approach that takes vibration behaviour into consideration. Accordingly, future research ought to consider the extent to which other product modelling approaches on both sides could also be linked or even the consideration of a different functional behaviour

can be enabled. A different approach to taking vibration behaviour into consideration could possibly reduce the significant simplification resulting from the SDOF system approach.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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