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A hypothesis-based method for building specific design knowledge for robust design

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ABSTRACT: Robust Design (RD) is crucial in product development to ensure that products maintain reliable performance under varying conditions. Design knowledge is fundamental to RD. However, current methods lack a systematic approach to support design engineers in building design knowledge for RD. This paper addresses this gap by introducing a hypothesis-based method for systematically building design knowledge for RD. RD hypotheses are specifically developed for this purpose and are tested through a five-step method. The application of this method is demonstrated in a case study involving a hand-operated coining machine. The results show that the proposed method supports building specific design knowledge through two RD hypotheses. By employing this method, design engineers are systematically supported in making design decisions, leading to more robust product concepts.

KEYWORDS: robust design, design methods, embodiment design, product development, design knowledge

1. Introduction

Ensuring reliable functional fulfillment of a product is a fundamental goal of product development. Deviations, such as those caused by manufacturing errors or wear and tear during use, can lead to reduced functional fulfillment and increased cost. The robustness of a product, defined as its ability to withstand such deviations, is therefore critical to maintaining long-term customer satisfaction and business success. Robust Design (RD) addresses this challenge by designing a product that is insensitive to such deviations (Taguchi et al., 2005). Its importance in modern product development continues to grow, as the industry seeks cost-effective and reliable solutions (Eifler et al., 2023). Particularly in the early stages of product development, robustness must be a critical consideration for design engineers in the decision-making process. Designing a highly robust product requires a thorough understanding of the technical system, which in turn requires specific design knowledge (Hubka & Eder, 1990).
Although various RD methods are available to help design engineers make robust design decisions (Ebro & Howard, 2016), they are often based primarily on expert-based design principles without specific reference to the product being developed. These methods often lack the ability to systematically support design engineers in building the specific design knowledge needed to make informed decisions. This is particularly challenging when addressing whether the designed system can fulfill its functions over the estimated lifetime. As a result, decision-making in the design of robust and reliable products remains a challenge for design engineers. To address this problem, this paper explores the following research question:

> *How can specific design knowledge for RD be built methodically in the early stages of product development?*

This paper aims to propose a hypothesis-based method to support design engineers in systematically building specific design knowledge for RD, facilitating the derivation of robust design solutions. Section 2 reviews related work on design knowledge with a focus on robust design. In Section 3, we present our proposed method to answer the research question. To illustrate the application of the method, a case study is presented in Section 4. The results are discussed in Section 5 and concluded in Section 6.

2. Related work

Dealing with different forms of knowledge is essential for successful product development (Pitt & MacVaugh, 2008). During the development process, it is crucial to structure knowledge and its potential interconnections to facilitate decision-making (Roth et al., 2010). Modern products are typically developed in generational iterations (Albers & Rapp, 2022), making effective knowledge transfer between generations essential for continued success (Pahl et al., 2007). In general, knowledge can be categorized into explicit and implicit knowledge (Dzbor & Zdráhal, 2001; Luft et al., 2017).While explicit knowledge is easily accessible through technical documents, implicit knowledge remains personal and intuitive (Luft et al., 2017). Design decisions often rely heavily on implicit knowledge (Ahmed et al., 2005; Shabi & Reich, 2012). Understanding and managing both forms of knowledge is critical for informed decision-making and robust product development.

In order to make targeted decisions in the design process, specific design knowledge is essential (Hubka & Eder, 1990). Matthiesen et al. (2024) define specific design knowledge as knowledge about the relation between characteristics of the embodiment and the functional behavior of the system to be designed. Characteristics are defined according to Weber (2014) as parameters that can be directly influenced by design engineers. In our context, we consider characteristics assigned to the domain of the structure according to the Function-Behavior-Structure (FBS) ontology by Gero and Kannengießer (2014). Understanding this relation enables the decision-making in design to achieve the desired functional behavior. When focusing on building specific design knowledge for RD, deviations from the desired design must also be considered (Hasenkamp et al., 2009).

To increase the robustness of a product against deviations, traditional RD methods focus on the later design stages by optimizing the parameter or tolerance design (Taguchi et al., 2005). However, the early design stages, where various design decisions are made to define the preliminary product geometry, have a critical impact on the robustness of a product (Eifler & Schleich, 2021). Early-stage RD methods, such as those based on RD principles (Ebro & Howard, 2016; Horber et al., 2024; Li et al., 2023), leverage research-based and experiential knowledge. The contradictory nature due to the large number of these principles complicates their direct application to individual design objects. Some approaches (Goetz et al., 2019) aim to assess multiple RD principles, but do not clarify how specific characteristics influence the functional behavior. Therefore, these approaches are not efficient for building specific design knowledge for a robust product design. To generate knowledge for RD in early design stages, various approaches can be employed, i.e., Design Structure Matrix (Eppinger & Browning, 2012) or Axiomatic Design (Suh, 1998). These approaches emphasize system architecture and knowledge structuring in product development but provide limited support for design decision-making due to their focus on system-level relationships rather than design characteristics.

One approach that directly supports the building of specific design knowledge is the Contact and Channel Approach (C&C^2-A) (Grauberger et al., 2019). This approach introduces the state modeling technique to investigate system behavior by identifying added and removed working surface pairs (WSPs) in different system states, taking into account embodiment characteristics (Grauberger et al., 2022; Kleinhans et al., 2024; Matthiesen et al., 2019). However, this approach requires further exploration for its application in RD. Furthermore, awareness of deviations is essential in RD (Hasenkamp et al., 2009). While tools such as Variation Mode and Effect Analysis (VMEA) (Johansson et al., 2006) can support the analysis of deviations and their potential effects, they do not explain the specific design knowledge behind the assumptions made, as they do not focus on the embodiment characteristics. The Embodiment-Function-Relation and Tolerance (EFRT) model extends the C&C^2-A by incorporating geometric deviations into system behavior analysis (Li et al., 2024). However, no systematic method has yet been established to build specific design knowledge for RD.

In statistics, hypotheses are often used to structure a systematic investigation of knowledge. This process includes the creation of hypotheses that can be verified or falsified through testing (Bortz & Döring, 2006). Based on this approach, design hypotheses were proposed, which can be examined through testing to generate specific design knowledge (Matthiesen et al., 2017). These hypotheses describe the relations between characteristics of the embodiment and the functional behavior of a system behind these relations using an "easy to remember" scheme: if (description of change in characteristics of the embodiment), then (description of change in functional behavior), because (hypothesized cause for the relation between characteristics of the embodiment and functional behavior). This scheme facilitates the documentation of specific design knowledge. Current design hypotheses do not account for deviations, which require modifications of the formulation for their application in RD.

Like hypotheses in general, design hypotheses need to be tested to gain reliable knowledge from them. Early-stage testing is desirable to obtain empirical data on functional performance, but can be challenging due to the lack of a finished design (Engel, 2010). Testing processes often require significant project resources (Liewerenz et al., 2023). To reduce these resource demands, less resource-intensive manufacturing techniques, such as 3D printing, are used for early-stage testing (Lachmayer & Lippert, 2017). In empirical testing, surrogate models can be used that comprise comparable characteristics to the original product being tested (Peters et al., 2024). This facilitates more efficient exploration of design hypotheses, while conserving resources and allowing for faster iteration in the design process.

In summary, the state of the art highlights the importance of formulating design hypotheses as a means to systematically build up specific design knowledge. The development of a new method for building specific design knowledge for RD refers to the potentials of the C&C^2-A in combination with hypothesis-based testing. The C&C^2-A offers the uniqueness of modeling of relation between characteristics of the embodiment and functional behavior. This usually facilitates the understanding of the system, as well as decision-making in design. These hypotheses must be tested to validate their applicability and ensure reliable knowledge generation. While this approach is well-suited for integration into RD, it requires adaptations to account for deviations. Techniques such as state modeling with C&C^2-A (Grauberger et al., 2022) and EFRT sketches incorporating deviations (Li et al., 2024) provide valuable tools for analyzing system behavior under varying conditions. These methods allow for a detailed examination of the effects of deviations on system performance. However, further research is necessary to combine these techniques into a structured method that integrates hypothesis formulation, modeling, and early testing.

3. A hypothesis-based method for building specific design knowledge for robust design

Based on the state of the art, we have combined the design hypothesis, state modeling from the C&C^2-A, and early testing into a structured method to systematically support the building of specific design knowledge for RD. This method is applicable during early design stages, when a concept exists and the embodiment characteristics need to be pre-determined by the design engineers, but optimized parameterization of the characteristics is not required.

Specific design knowledge for RD is defined in this paper as the understanding of the relations between the occurring deviations of the characteristics and the functional behavior of a technical system. The method consists of five iterative steps to generate design hypotheses for RD, accompanied by testing to examine them (see Figure 1). Through the steps, specific design knowledge for RD is built continuously.

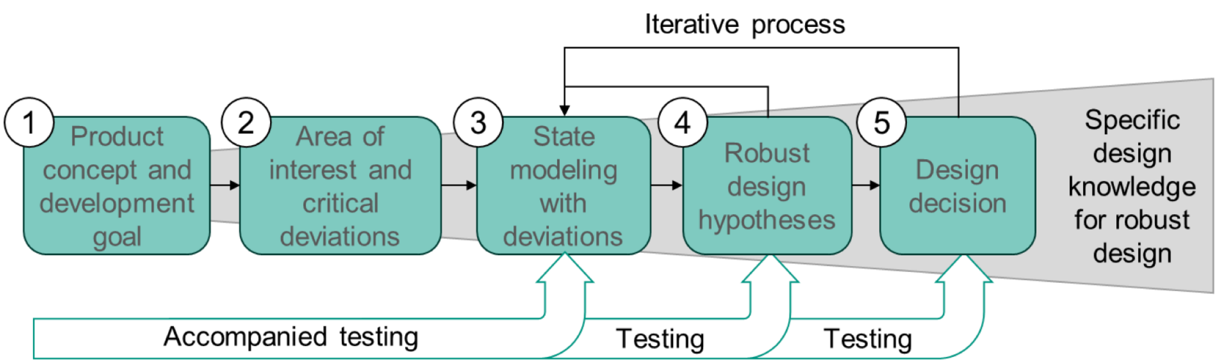

Figure 1. A five-step iterative method for building specific design knowledge for robust design

Step 1 is the **analysis of the current product concept in relation to the development goal**. The aim of this step is to establish a problem statement of the current product concept and to define the development goal. The development goal must be precisely defined, incorporating relevant aspects from the requirements list or specification document. It is crucial to identify the functions that must be fulfilled to meet the development goal and determine suitable evaluation criteria for assessing functional fulfillment. Accordingly, the current product concept must be analyzed concerning the development goal, with a focus on how the current solution qualitatively fulfills the desired functions. Furthermore, the problem statement must be clarified in terms of the development goal: either there is a concrete problem from the previous product generation, or the potential problem has to be identified in the new development project. The output of Step 1 is the understanding of how the product concept fulfills its intended function, and the specific problems need to be addressed in subsequent development steps.

Step 2 focuses on identifying the **Area of Interest (AoI) and the critical deviations** affecting it. The AoI refers to the location of functional fulfillment within the product concept. The aim of this step is to define the object of observation and narrow it down from the overall system. After the overall product concept has been analyzed in Step 1, the specific AoI where the function is fulfilled must be identified. This area should be carefully delineated to reduce the scope and effort of the analysis. To facilitate this analysis, the C&C^2-A can be used to trace the load path within the system and identify the relevant interactions that contribute to functional fulfillment. Another focus of this step is to identify the critical deviations that can lead to reduced functional performance and assess their probability of occurrence. The output of this step is a clearly defined AoI, represented through an appropriate sketch. It also includes the critical deviations to be addressed in further development.

Step 3 focuses on **state modeling with deviations**. The aim of this step is to analyze how functional fulfillment is influenced by the identified deviations. This is done by examining the function-relevant system behavior under critical deviations through state modeling. The previously identified deviations are introduced into the defined sketch from step 2 (see also (Li et al., 2024)). These deviations lead to changes in the system behavior that differs from the desired state, which can also be analyzed using C&C^2-A. This change in system behavior is analyzed to determine how the observed deviation impairs functional fulfillment, potentially using established knowledge such as physical laws (Mathias et al., 2011). Testing with appropriate surrogate models, such as rapid prototypes, can verify the accuracy of the state modeling. The output of this step is different system states that reflect the functional behavior and the critical system state caused by deviations.

Step 4 involves building and examining **RD hypotheses**. The aim of this step is to investigate the assumed critical states from step 3 and identify characteristics and their relations to the functional behavior. These relations are described using RD hypotheses derived from the design hypotheses. The output of this step consists of the formulated and examined RD hypotheses.

First, relevant characteristics are identified by analyzing the critical states resulting from the deviations, based on the knowledge gained in Step 3. Then, RD hypotheses relating to these design characteristics are formulated. This paper proposes RD hypotheses by adapting the formulation of general design hypotheses outlined by (Matthiesen et al., 2019). RD hypotheses are structured as follows:

> ***Robust Design hypothesis: under a given deviation, if*** *(description of the change of a characteristic), then (description of the hypothesized change in functional behavior),* ***because*** *(description of the relations between characteristic and functional behavior).*

The formulation of RD hypotheses involves making assumptions about how the interaction between changes in characteristics can impact functional fulfillment under given deviations. These assumptions must be possible to be evaluated through testing (model-based or empirical). It is essential to consider the critical deviations identified in Step 2, as these deviations directly impact functional fulfillment and interact with the characteristics. Formulating these hypotheses is an iterative process between Steps 3 and 4, where the insights from state modeling in Step 3 continuously inform and refine the hypothesis development. This iterative cycle is repeated until sufficient clarity is achieved to support a robust design decision.

For testing purposes, the surrogate model developed in Step 3 continues to be used in this step. Additionally, deviations must now be incorporated into the surrogate model to enable testing of the hypothesized relations.

Step 5 focuses on making **design decisions** using the gained design knowledge for RD. The aim of this step is to apply the accumulated specific design knowledge to synthesize a robust solution aligned with the development goal. Through the formulation and testing of RD hypotheses, specific design knowledge for RD continuously increases, particularly regarding how the functional behavior changes when characteristics are modified through deviations in specific ways. This knowledge is leveraged to make informed design decisions and derive the final concept. It is recommended to validate the derived final concept through testing to assess the interactions among the characteristics. If the desired function is not fulfilled, the process returns to Step 3, where state modeling and hypothesis refinement occur. The output of Step 5 is a finalized product concept, alongside the gained specific design knowledge for RD.

4. Case study - hand-operated coining machine

The presented method is illustrated in this paper through a case study. The aim of the case study is to demonstrate how the method can be applied to a development project and what type of design knowledge for RD can be achieved. This case study focuses on improving the robustness of a hand-operated coining machine (see Figure 2 on the left). The working principle, shown in Figure 2 in the middle, involves manual operation to generate force by pressing the bars. This action moves a piston downward, which is guided by a cylindrical guide. During this downstroke, the piston mints a coin positioned on the bed. Once the minting process is complete, the system allows the minted coin to be released from the piston. The previous generation of the product exhibited a significant problem: coins were often minted crooked, resulting in poor coin quality. The goal of the case study is to adapt the design of the coining machine to ensure that the coins are minted straight.

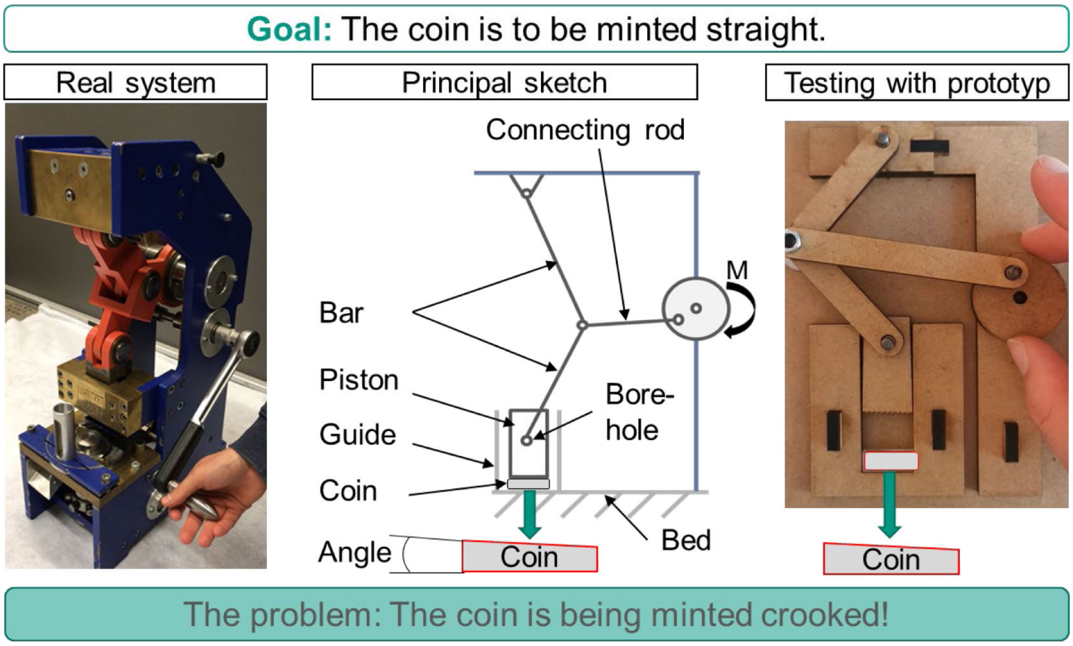

Figure 2. Case study of a coining machine, its principal sketch and prototype

For the accompanied testing, rapid prototypes were used to evaluate the formulated RD hypotheses. A prototype of the coining machine (see Figure 2 on the right) was manufactured using high-density fiberboards and a laser cutter machine. Plexiglass was used to simulate the resistance caused by the coin. To investigate the effect of deviations, these were manually introduced into the prototype and exaggerated for clarity. The detailed execution of the process is outlined in the subsequent steps, illustrating how RD hypotheses are built and examined with testing.

Step 1: The problem with the previous product was that the coins were minted at an angle, resulting in low quality. The development goal is to mint the coins straight (see Figure 2). For a better understanding of the product concept, its principal sketch is drawn in Figure 2. To quantify the functional fulfillment, the angle of the minted coin can be defined as an evaluation criterion, as shown in Figure 2.
Step 2: The AOI is defined within the coin minting region (see Figure 3 on the left). To narrow down the Area of Interest, C&C^2-A elements are used for analysis. The WSP between the piston and guide, as well as the WSP between the piston and coin, are directly relevant to the coin's minting angle. Thus, the Area of Interest is constrained within the marked region. Using the channel and support structure (CSS), the load path within the AoI is tracked. The force input and other boundary conditions outside the AoI can be modeled using Connectors. A critical deviation is identified as the piston shape deviation (see Figure 3 on the right), which frequently occurs due to wear on the right side of the piston in the previous product generation. This deviation is expected to impact the minting process and must be analyzed to identify its effect on functional fulfillment.

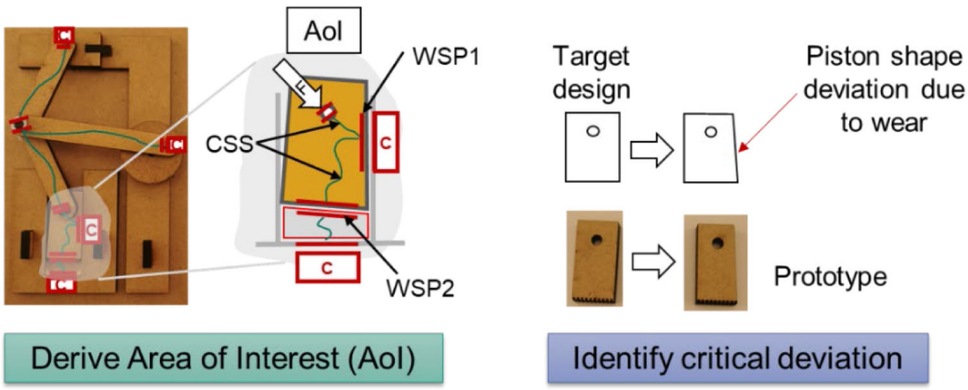

Figure 3. Area of Interest and critical deviation in the coining machine example. (WSP: Working Surface Pair, CSS: Contact and Support Structure, C: Connector)

Step 3: Various states in the coining process can be identified. Three key states are particularly important: guiding, contact, and minting (see Figure 4: State modeling). The first two states define the system behavior before the minting process, and the minting state is directly relevant to functional fulfillment and requires special attention.

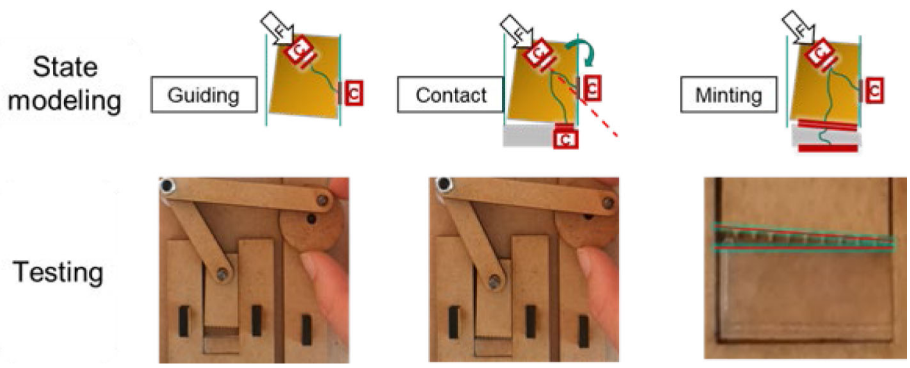

Figure 4. State modeling and initial testing of the coining machine with piston shape deviation

The skewed force input causes the piston to be pressed against the right side of the guide, creating a WSP between the piston and guide. During the minting process, the piston either returns to the center position due to the resistance from the coin or remains skewed against the guide because of the tilting moment generated by the skewed force input. Due to the introduced piston shape deviation, the state is modeled as the coin being minted at an angle, with the assumption that the piston remains skewed.These states are then examined with testing using the prototype introduced above (see the testing section of Figure 4).

During the minting process of the prototype, the angle between the bottom of the piston and the coin is observed to assess the accuracy of the state modeling. As a result, testing of the coining machine confirms the state modeling, showing that the bottom of the piston remains skewed throughout the minting process.

Step 4: Two RD hypotheses are formulated for the coining machine based on the insights gained from state modeling. State modeling revealed that the tilting moment on the piston plays a significant role in the skewed minting process. This tilting moment arises from the combination of force components and the lever arm. It is hypothesized that modifying the angle and the point of force application could mitigate the skewing. The characteristic responsible for the angle of force application is the connecting rod length, and for the point of force application is the borehole position (see Figure 5). With these two characteristics identified, two RD hypotheses were formulated as follows:

RD Hypothesis 1: Under the given piston shape deviation, if *the length of the connecting rod is shortened (characteristic),* ***then*** *the coin will be minted more evenly (functional behavior),* ***because*** *the shortened length reduces the angle of force application during the "minting" state, which causes the piston to return to the center instead of staying skewed (relation between characteristic and functional behavior).*

RD Hypothesis 2: Under the given piston shape deviation, if *the bore position is moved closer to the piston bottom (characteristic),* ***then*** *the coin will be minted more evenly (functional behavior),* ***because*** *the reduced lever arm decreases the torque, preventing the piston from being pushed out of alignment during the minting process (relation between characteristic and functional behavior).*

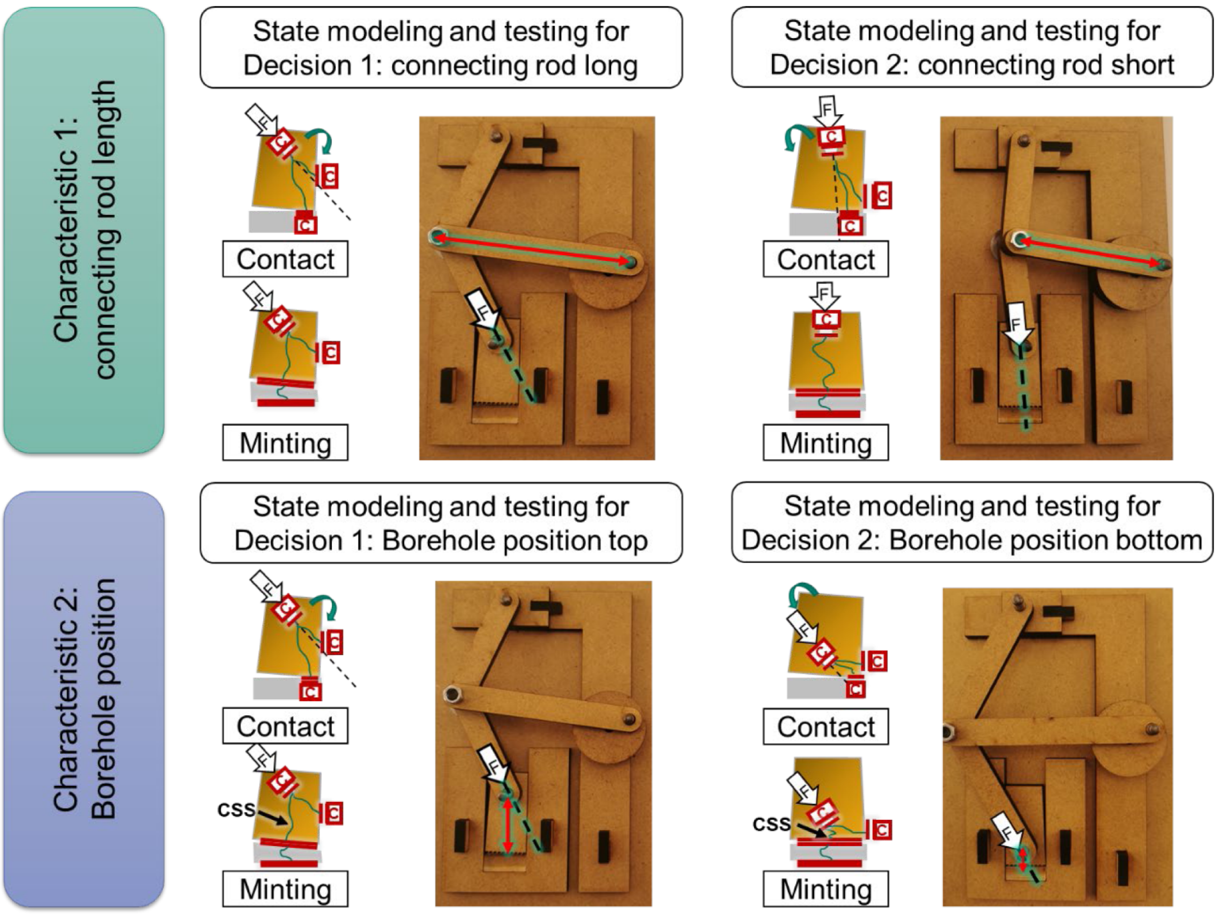

Figure 5. State modeling regarding the two characteristics and testing to examine the hypotheses

These hypotheses can now be evaluated through testing (see Figure 5). Adjustments to the connecting rod length and bore position were made in the prototypes, and the states were tested again. The testing results confirmed the hypotheses: by modifying these characteristics, the piston was positioned centrally during minting, resulting in a straight coin.

Step 5: The specific design knowledge for RD has been built through the formulation and testing of RD hypotheses. Key insights from the previous step were:

- A concept with a shorter connecting rod is more robust against the given piston shape deviations.
- A concept with a borehole positioned lower on the piston is more robust against the given piston shape deviations.

Based on these findings, a final concept was derived, which incorporates both a shorter connecting rod and a lower bore position (see Figure 6). It is still crucial to examine the concept through further testing. The derived concept was tested with the updated characteristics, and the results of these tests were consistent with the expected improvements. The piston remained centered during the minting process.

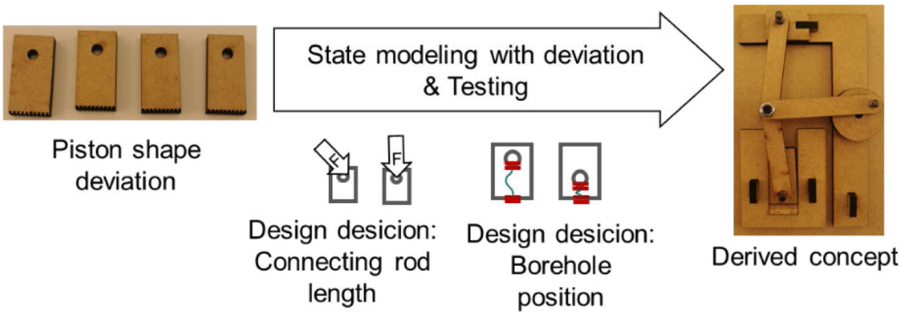

Figure 6. Deriving a new concept for testing to make the design decision

5. Discussion

The results of the case study show that the research question *"How can specific design knowledge for RD be built methodically in the early stages of product development?"* can be answered with the proposed method. From the example of the coin minting machine shown above, it can be deduced that the systematic building and testing of RD hypotheses enables designers to build and document specific design knowledge for RD. This is achieved in the five steps of the described method, which serve as a guide for design engineers. The prototype of the product concept visually illustrates the design deviations and their effects on functional behavior. The combination of formulation and testing of the RD hypotheses supports decision-making in the design of robust mechanical product concepts in the early phases of product development.

The described method can extend and support existing RD methods e.g. from Ebro and Howard (2016) or Goetz et al. (2019) through its ability to directly transfer and modify RD hypotheses in relation to characteristics. Compared to late-stage RD methods, such as those by Taguchi et al. (2005), the proposed method allows for earlier knowledge acquisition. In addition, this approach enables an extended usability of the C&C^2-A (Grauberger et al., 2022) and the EFRT model (Horber et al., 2022) by providing a systematic approach to build specific design knowledge for RD.

Furthermore, the new method allows for early testing of the impact of deviations in characteristics on system behavior using cost-effective prototypes. The prototypes represent a special part of a complex overall system that will be examined in detail. The effects of changes can be directly observed and quantified through targeted testing methods. Hypothesis-based testing offers a more affordable and quicker execution, while fostering the accumulation of specific design knowledge and driving substantial improvements to the design.

The limitation of the proposed method lies in the representation of the fidelity of the prototype in empirical testing. The simplified prototypes refer specifically to the development of knowledge about the functional behavior of a system, whereby a high fidelity and number of parameters are not expedient and should be avoided. In addition, the testing environment is adapted to the surrogate model, so that the model properties deviate from the real conditions (Peters et al., 2024). It is impossible to account for all unknown factors in the prototype. Therefore, only the critical deviations are incorporated into the surrogate model. The findings gained through the proposed method must be transferred to the real system in the later development stages. For the future further development of the method, the long-term storage of the acquired knowledge is necessary. In addition, it is conceivable not only to present system-specific knowledge transparently, but also to make it available via general design rules.

6. Conclusion

RD plays a critical role in product development by enabling cost reduction and improving product quality. Specific design knowledge is essential to achieve higher robustness through design, as the knowledge provides the foundation for informed decision-making. This paper presents a hypothesis-based method for systematically building specific design knowledge for RD. For this purpose, RD hypotheses were developed and applied within a structured five-step method that facilitates their formulation, testing, and refinement. The application of the method was demonstrated through a case study of a hand-operated coining machine, confirming that specific design knowledge for RD can be methodically built. The results show that the proposed method enables the continuous enhancement of design knowledge for RD. This method supports design engineers in building the necessary design knowledge to make informed decisions, enhancing the potential for creating robust and reliable product concepts.

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