Karlsruhe Institute of Technology

Design Robustness Index for Evaluating the Robustness of Product Concept

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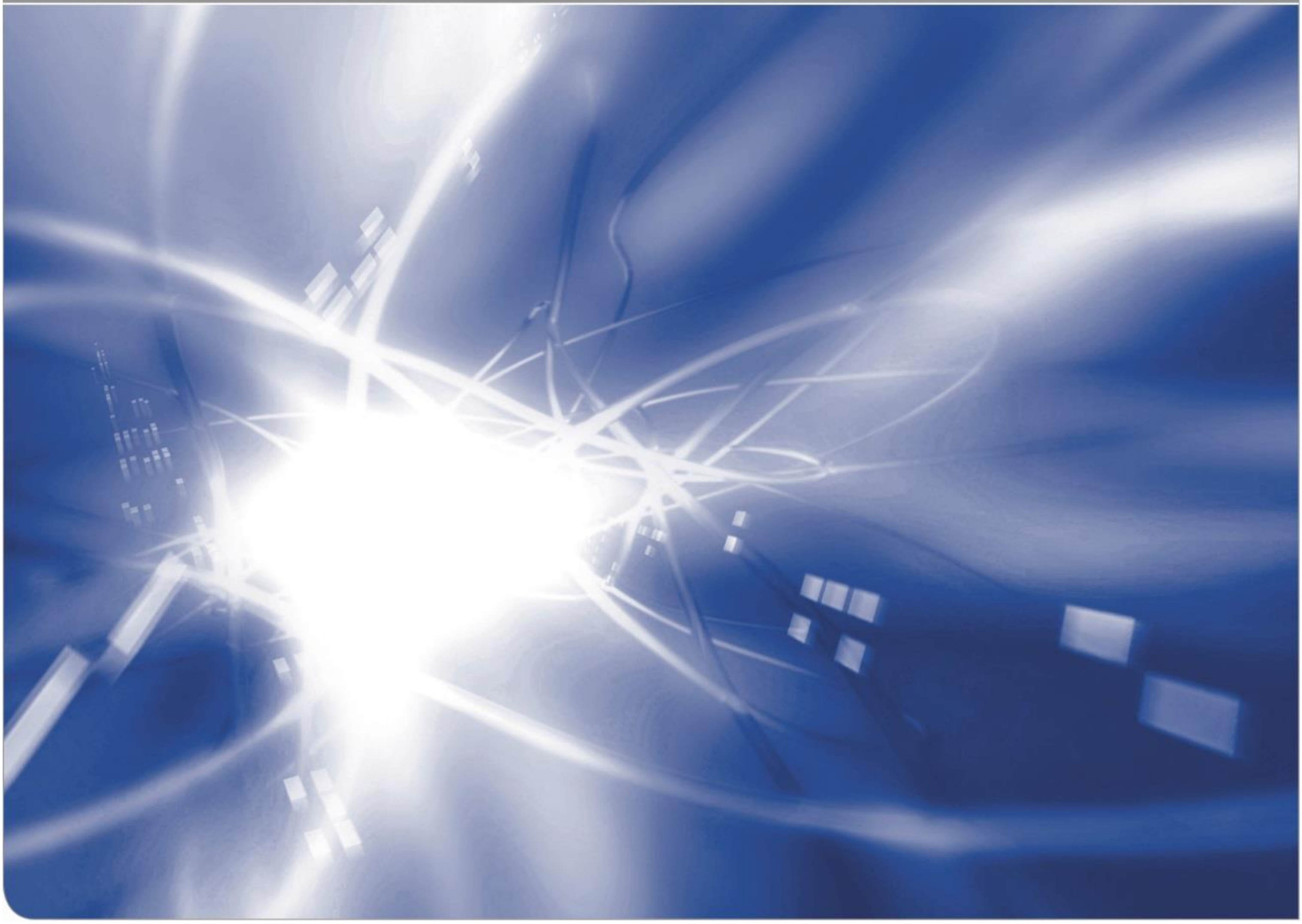
KIT SCIENTIFIC WORKING PAPERS 255



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1. Introduction

Robustness against geometric deviations is a key success factor in product development, especially in the early design stages where it has a significant impact on product cost [1–3]. Numerous Robust Design (RD) methods have been developed to address deviations in the early design stages [4–9]. The Embodiment Function Relation and Tolerance (EFRT) model provides a comprehensive framework for linking geometric deviations to functional fulfillment [10], and its potential has been demonstrated through subject studies and case applications [11, 12].

Following the EFRT-based method [13], this work derives the Design Robustness Index (DRI) as a quantitative measure to evaluate the robustness of product concepts against geometric deviations. Here, 16 different coining machine concepts are evaluated using the EFRT-based method, resulting in corresponding DRIs. Early experimental testing was conducted to validate the robustness evaluation. This document presents the results of the robustness evaluation and its initial testing, providing research data for further analysis and insights.

2. Materials and methods

The description of materials and methods is based on [13]. Figure 1 illustrates the 16 coining machine concepts, differentiated by four characteristics: connecting rod length (long/short), borehole position in the piston (top/bottom), guide element length (long/short), and guide connection (to bed/frame). The robustness of these concepts against general deviations and two specific deviations (piston shape deviation and clearance deviation) is evaluated using the EFRT-based method, resulting in 16 DRIs. Each DRI is calculated with one Graph Index and two Sketch Indices.

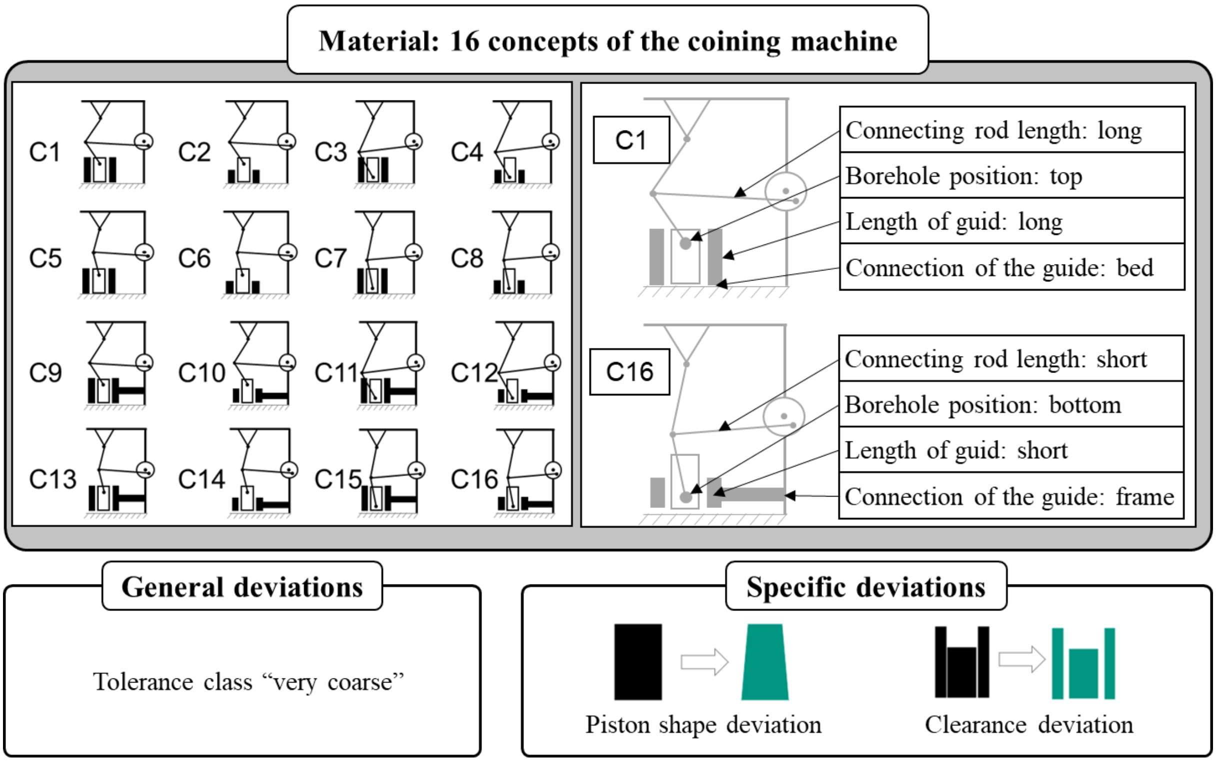


Figure 1. Different concepts of the coining machine for robustness evaluation according to [13]

The Sketch Indices are calculated based on assumed system states, necessitating initial validation. CAD-based surrogate models of Concepts 1-8 were created and manufactured using rapid prototyping (see Figure 2). Surrogate models possess physical properties that closely resemble those of the real system, making them well-suited as testing objects [14]. Concepts 9-10 have identical Sketch Indices to Concepts 1-8. Therefore, they are not included in the test. Prototypes were made from high-density fiberboard using laser cutting, while a plastic-deforming modeling compound was chosen as the coin material. Three tests were conducted for each concept: with ideal CAD geometry, with a 5° piston shape deviation, and with a 2 mm clearance deviation. The piston shape deviation was modeled by tilting the bottom edge of the piston 5° relative to the side edge, while the clearance deviation was simulated by increasing the guide width by 2 mm. Before testing, the coin material was cut into uniform pieces and minted using the prototypes. The angle between the coin's upper and lower surfaces was measured graphically by photographing the minted coins in a fixed camera stand. Each test was repeated three times to minimize errors, with the median value taken to exclude outliers. The measured coin angles from the tests are then compared to the theoretically evaluated Sketch Indices for the initial validation. The initial validation of the Graph Indices can be found in [13].

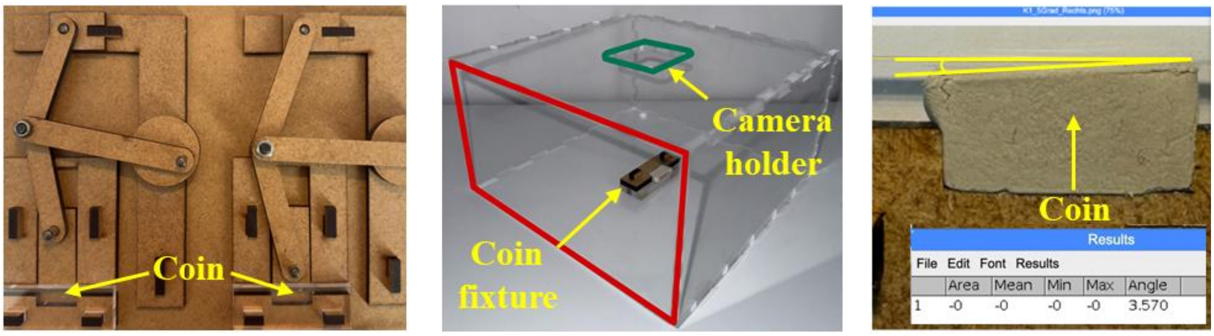


Figure 2. Experimental set-up for initial validation of the Sketch Indices according to [13]

3. Results

3.1 Results of robustness evaluation

The results of the robustness evaluation are shown in Figures 3-10 below. Key Characteristic (KC) is used as a measure of functional fulfillment. For the coining machine, the KC is the angle between the coin's upper and lower surfaces. The ideal KC value is 0°. Deviations from this value indicate a reduction in functional fulfillment. The impact of the given general and specific deviations on the KC needs to be evaluated. EFRT graphs and EFRT sketches are then built. The EFRT graph models the system structure using geometry elements, and the EFRT sketch models the system behavior using working surface pair (WSP), contact and support structure (CSS), and connector (C). Both the EFRT graph and sketch model the KC and deviations. The Graph Index is calculated as the ratio of the number of geometry elements in the EFRT graph of a concept to the number in the concept with the longest chain, while the Sketch Index evaluates the KC deviation of a concept relative to the maximum deviation across all concepts within the EFRT sketch. Based on the experience of previous product generation, the following weighting factors were assigned: Graph Index was given a weight of 4, Sketch Index for piston shape deviation was given a weight of 2, Sketch Index for clearance deviation was given a weight of 3. These indices were then combined to calculate the DRI by summing their values, each multiplied by its respective weighting factor. A more detailed description of the evaluation can be found in [13].

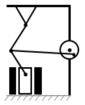
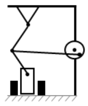
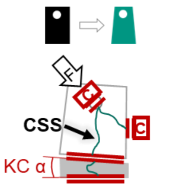
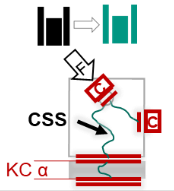
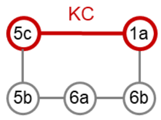
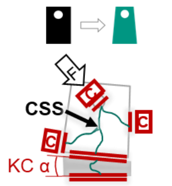
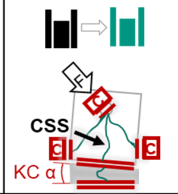
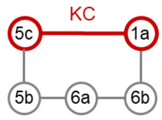
Concept	**Concept 1** 			**Concept 2** 		
EFRT modeling	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 
Indices	SI_1=5°/6°=0.83	SI_2=0.5°/5°=0.10	GI=5/8=0.63	SI_1=6°/6°=1.00	SI_2=5°/5°=1.00	GI=5/8=0.63
Weighting	2	3	4	2	3	4
DRI	**4.5**			**7.5**		

Figure 3. Robustness evaluation of Concept 1 and Concept 2

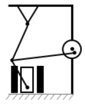
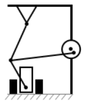
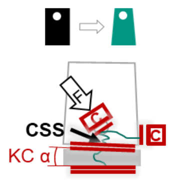
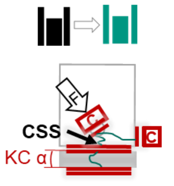
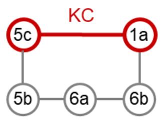
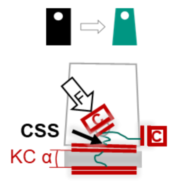
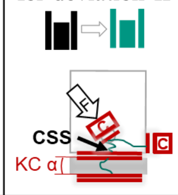
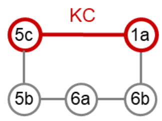
Concept	**Concept 3** 			**Concept 4** 		
EFRT modeling	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 
Indices	SI_1=3°/6°=0.50	SI_2=0.5°/5°=0.10	GI=5/8=0.63	SI_1=3°/6°=0.50	SI_2=0.5°/5°=0.10	GI=5/8=0.63
Weighting	2	3	4	2	3	4
DRI	**3.8**			**3.8**		

Figure 4. Robustness evaluation of Concept 3 and Concept 4

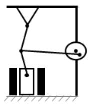
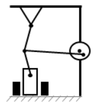
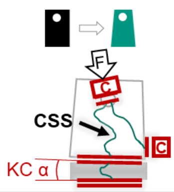
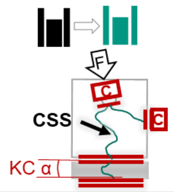
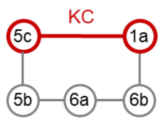
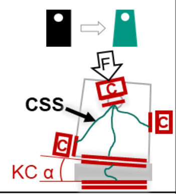
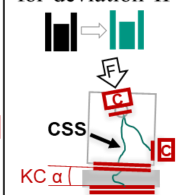
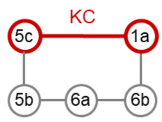
Concept	**Concept 5** 			**Concept 6** 		
EFRT modeling	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 
Indices	SI_1=2°/6°=0.33	SI_2=0.5°/5°=0.10	GI=5/8=0.63	SI_1=6°/6°=1.00	SI_2=1°/5°=0.20	GI=5/8=0.63
Weighting	2	3	4	2	3	4
DRI	**3.5**			**5.1**		

Figure 5. Robustness evaluation of Concept 5 and Concept 6

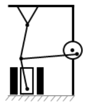
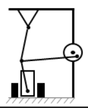
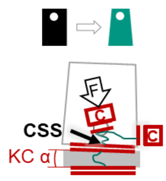
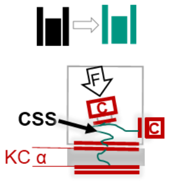
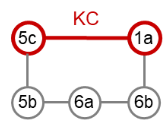
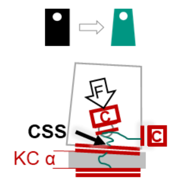
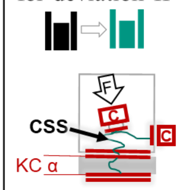
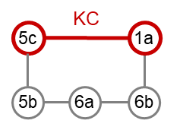
Concept	**Concept 7** 			**Concept 8** 		
EFRT modeling	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 
Indices	$SI_1=2°/6°=0.33$	$SI_2=0.5°/5°=0.10$	GI=5/8=0.63	$SI_1=3°/6°=0.50$	$SI_2=0.5°/5°=0.10$	GI=5/8=0.63
Weighting	2	3	4	2	3	4
DRI	**3.5**			**3.8**		

Figure 6. Robustness evaluation of Concept 7 and Concept 8

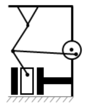
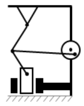
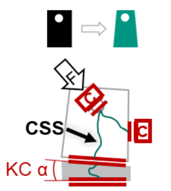
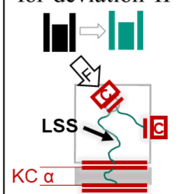
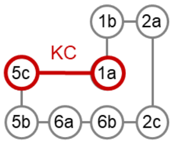
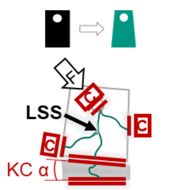
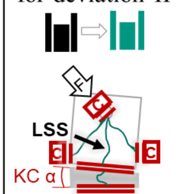
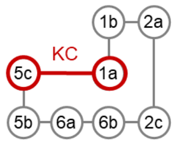
Concept	**Concept 9** 			**Concept 10** 		
EFRT modeling	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 
Indices	$SI_1=5°/6°=0.83$	$SI_2=0.5°/5°=0.10$	GI=8/8=1.00	$SI_1=6°/6°=1.00$	$SI_2=5°/5°=1.00$	GI=8/8=1.00
Weighting	2	3	4	2	3	4
DRI	**6.0**			**9.0**		

Figure 7. Robustness evaluation of Concept 9 and Concept 10

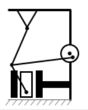
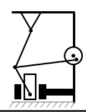
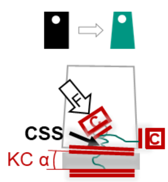
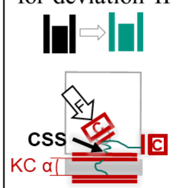
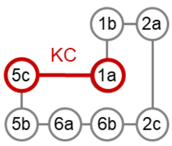
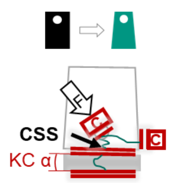
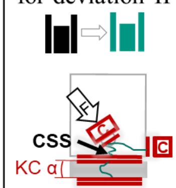
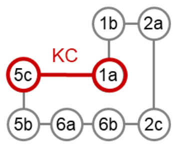
Concept	**Concept 11** 			**Concept 12** 		
EFRT modeling	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 
Indices	$SI_1=3°/6°=0.50$	$SI_2=0.5°/5°=0.10$	GI=8/8=1.00	$SI_1=3°/6°=0.50$	$SI_2=0.5°/5°=0.10$	GI=8/8=1.00
Weighting	2	3	4	2	3	4
DRI	**5.3**			**5.3**		

Figure 8. Robustness evaluation of Concept 11 and Concept 12

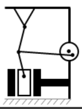
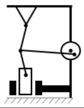
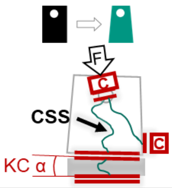
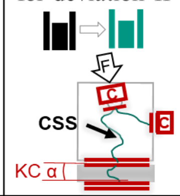
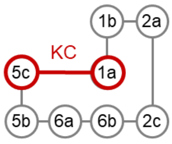
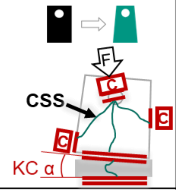
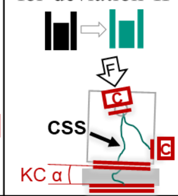
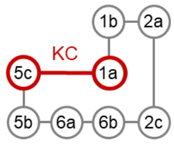
Concept	Concept 13 			Concept 14 		
EFRT modeling	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 
Indices	SI_1=2°/6°=0.33	SI_2=0.5°/5°=0.10	GI=8/8=1.00	SI_1=6°/6°=1.00	SI_2=1°/5°=0.20	GI=8/8=1.00
Weighting	2	3	4	2	3	4
DRI	**5.0**			**6.6**		

Figure 9. Robustness evaluation of Concept 13 and Concept 14

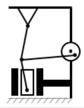
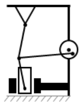
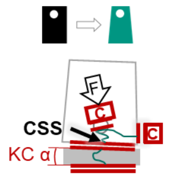
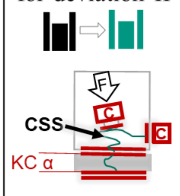
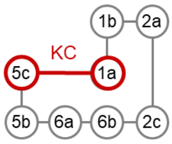
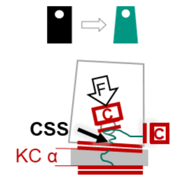
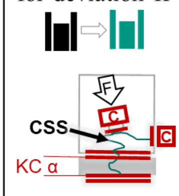
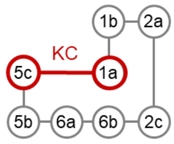
Concept	Concept 15 			Concept 16 		
EFRT modeling	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 	**EFRT Sketch I** for deviation I 	**EFRT Sketch II** for deviation II 	**EFRT graph** for general deviations 
Indices	SI_1=2°/6°=0.33	SI_2=0.5°/5°=0.10	GI=8/8=1.00	SI_1=3°/6°=0.50	SI_2=0.5°/5°=0.10	GI=8/8=1.00
Weighting	2	3	5	2	3	5
DRI	**5.0**			**5.3**		

Figure 10. Robustness evaluation of Concept 15 and Concept 16

3.2 Results of testing

The results of the experiments for the different concepts are presented in Figures 11–34. Testing results are shown sequentially for Concepts 1–8: first with the ideal CAD geometry, then with a piston shape deviation of 5°, and finally with a clearance deviation of 2 mm.

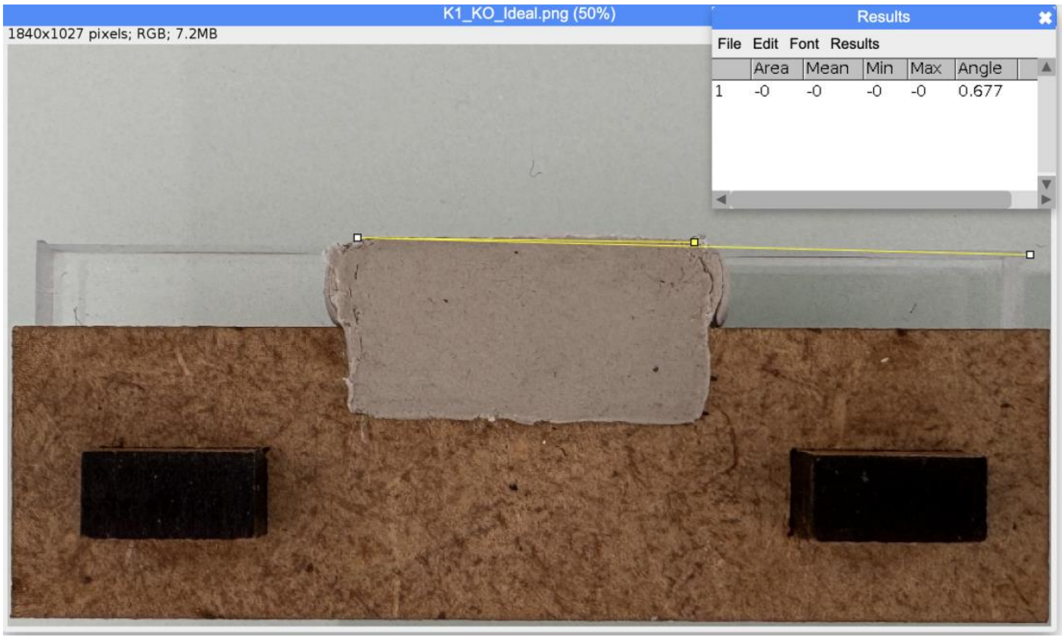


Figure 11. Testing result of Concept 1 with ideal CAD geometry: Coin angle = 0.68°

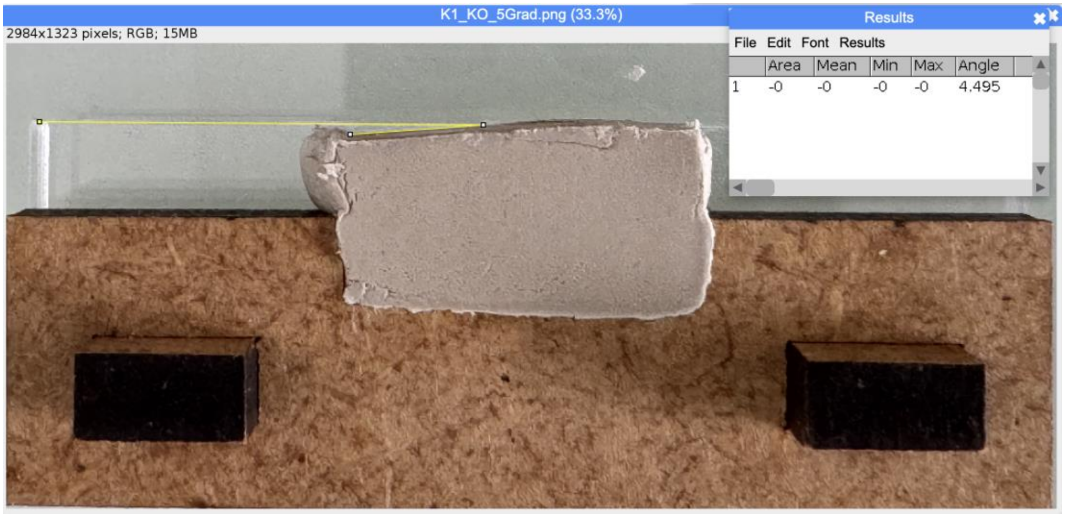


Figure 12. Testing result of Concept 1 with piston shape deviation 5°: Coin angle = 4.50°

Figure 13. Testing result of Concept 1 with clearance deviation 2mm: Coin angle = 0.67°

Figure 14. Testing result of Concept 2 with ideal CAD geometry: Coin angle = 0.92°

Figure 15. Testing result of Concept 2 with piston shape deviation 5°: Coin angle = 5.08°

Figure 16. Testing result of Concept 2 with clearance deviation 2mm: Coin angle = 6.53°

Figure 17. Testing result of Concept 3 with ideal CAD geometry: Coin angle = 0.64°

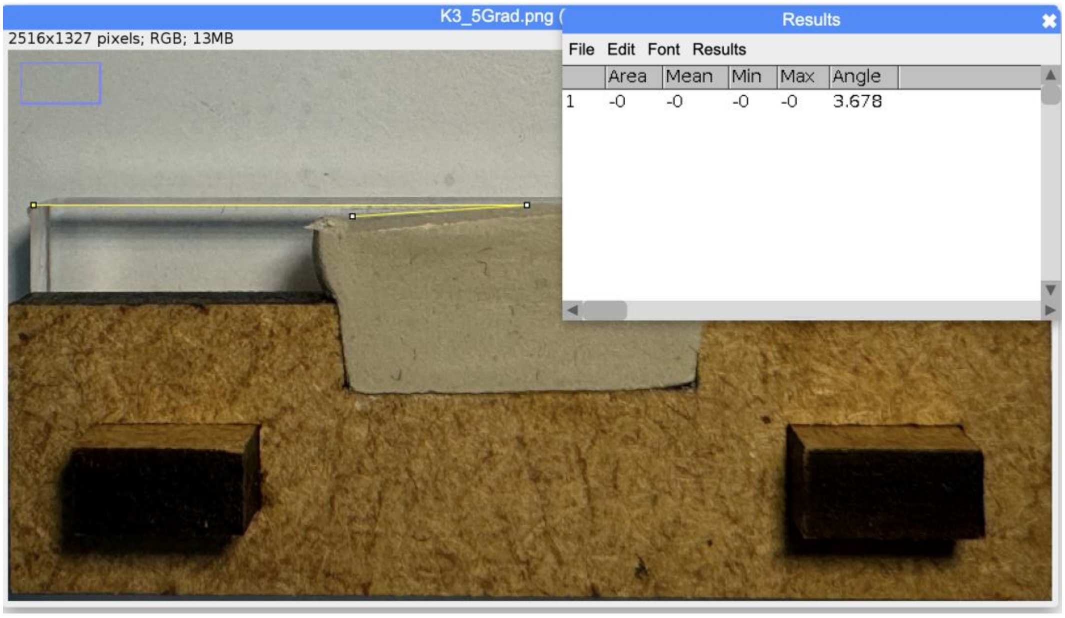


Figure 18. Testing result of Concept 3 with piston shape deviation 5°: Coin angle = 3.68°

Figure 19. Testing result of Concept 3 with clearance deviation 2mm: Coin angle = 0.88°

Figure 20. Testing result of Concept 4 with ideal CAD geometry: Coin angle = 0.59°

Figure 21. Testing result of Concept 4 with piston shape deviation 5°: Coin angle = 3.57°

Figure 22. Testing result of Concept 4 with clearance deviation 2mm: Coin angle = 1.07°

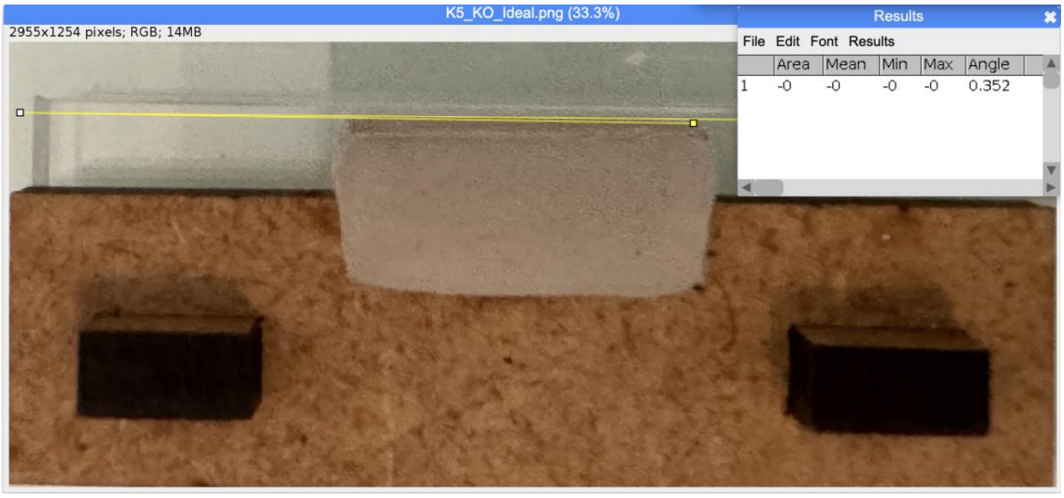


Figure 23. Testing result of Concept 5 with ideal CAD geometry: Coin angle = 0.35°

Figure 24. Testing result of Concept 5 with piston shape deviation 5°: Coin angle = 3.81°

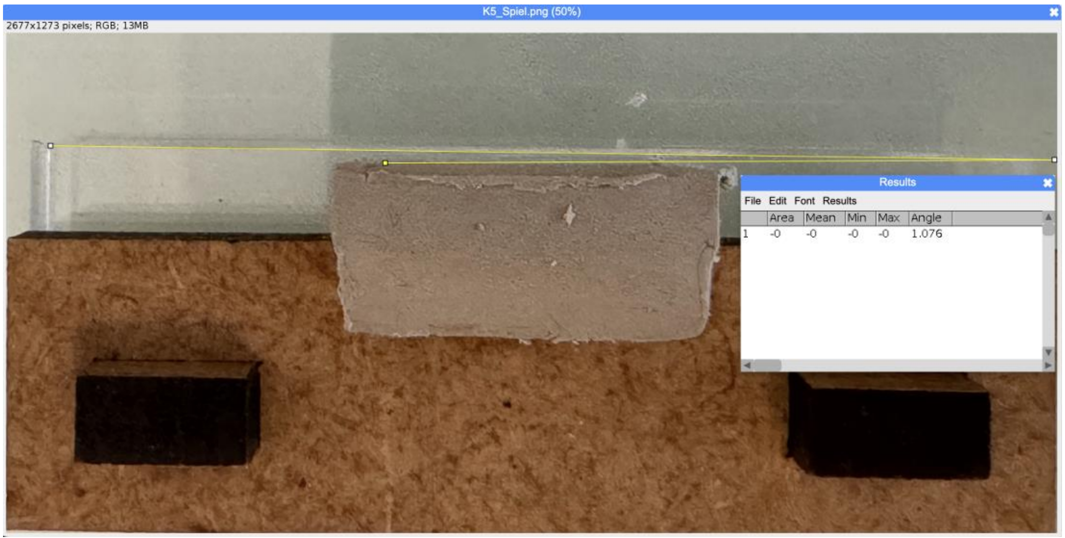


Figure 25. Testing result of Concept 5 with clearance deviation 2mm: Coin angle = 1.08°

Figure 26. Testing result of Concept 6 with ideal CAD geometry: Coin angle = 1.47°

Figure 27. Testing result of Concept 6 with piston shape deviation 5°: Coin angle = 6.11°

Figure 28. Testing result of Concept 6 with clearance deviation 2mm: Coin angle = 1.65°

Figure 29. Testing result of Concept 7 with ideal CAD geometry: Coin angle = 0.41°

Figure 30. Testing result of Concept 7 with piston shape deviation 5°: Coin angle = 2.78°

Figure 31. Testing result of Concept 7 with clearance deviation 2mm: Coin angle = 0.91°

Figure 32. Testing result of Concept 8 with ideal CAD geometry: Coin angle = 0.37°

Figure 33. Testing result of Concept 8 with piston shape deviation 5°: Coin angle = 3.80°

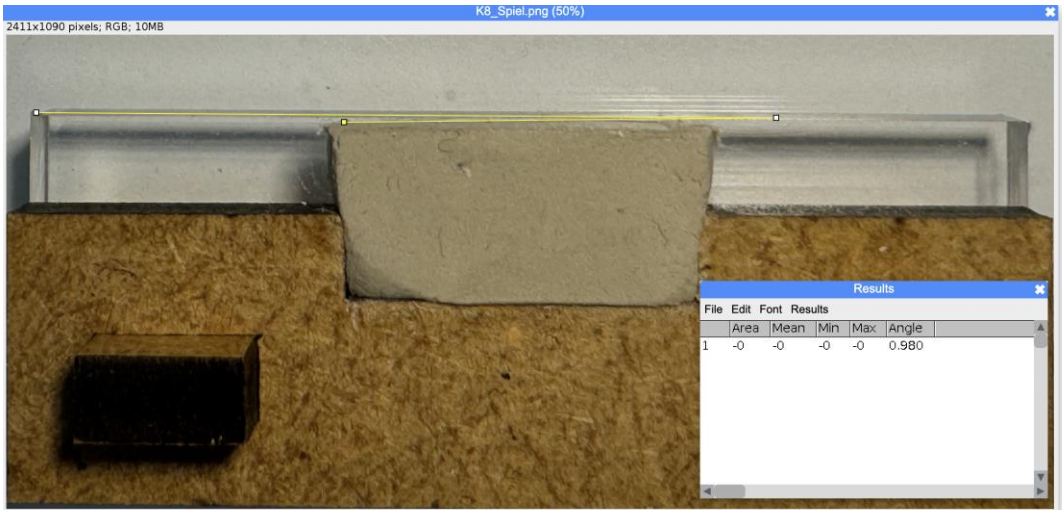


Figure 34. Testing result of Concept 8 with clearance deviation 2mm: Coin angle = 0.98°

3.3 Comparing the Sketch Indices and testing results

Table 1 compares the Sketch Indices and measured coining angles for Concepts 1-8, regarding both piston shape deviation and clearance deviation.

Table 1: Comparing the robustness evaluation with the results of testing.

	Concept	Robustness evaluation: Sketch Index	Results of testing: Experiment
Validation of Sketch Index for piston shape deviation	1	0.83	Coin angle 4.50°
	2	1.00	Coin angle 5.08°
	3	0.50	Coin angle 3,68°
	4	0.50	Coin angle 3.57°
	5	0.33	Coin angle 3.81°
	6	1.00	Coin angle 6.11°
	7	0.33	Coin angle 2.78°
	8	0.50	Coin angle 3.80°
Validation of Sketch Index for clearance deviation	1	0.10	Coin angle 0.67°
	2	1.00	Coin angle 6.53°
	3	0.10	Coin angle 0.88°
	4	0.10	Coin angle 1.07°
	5	0.10	Coin angle 1.08°
	6	0.20	Coin angle 1.65°
	7	0.10	Coin angle 0.91°
	8	0.10	Coin angle 0.98°

4. Discussion

The results demonstrate a strong alignment between the robustness evaluation and testing outcomes. However, exceptions were observed, such as in Concept 3 and Concept 5 regarding piston shape deviation. These discrepancies are primarily due to inaccurate assumptions about the system state, particularly regarding insufficient information about the friction behavior. Early-stage testing can effectively address this gap by providing empirical data. A more detailed discussion on this topic is presented in [13].

5. Conclusion

This study presents the robustness evaluation of 16 coining machine concepts, resulting in 16 DRIs. Each DRI comprises one Graph Index for general deviations and two Sketch Indices for the given specific deviations. Initial validation of the Sketch Indices has been performed through experimental testing using rapid prototyping, demonstrating good agreement with the theoretical robustness evaluation. However, limitations exist, including subjective assessments, measurement errors, and the fidelity of the surrogate models used for testing. Future comparisons with results obtained by other researchers or engineers applying the method to these concepts would be valuable for further validation.

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