COMPONENT SWAP ON VIRTUAL CATAPULTS FOR PROBLEM-SOLVING IN ENGINEERING EDUCATION

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ABSTRACT
This paper presents a web-based virtual catapult simulation to train the 'component swap' method in a quality management course, teaching Engineering students, especially those in engineering design and production engineering. In this method, components of two assemblies are systematically exchanged to analyse their effect on quality characteristics. While widely used in industrial problem solving in 'real' production setups, existing training with realistic applications, e.g. physical catapults, paper aeroplanes are resource intensive, sensitive to operator effects and constrained by logistical and accessibility barriers – often limited in teacher-centric education or training.
The virtual catapult replicates the original scenario with interchangeable components, automated data generation and configurable difficulty levels. A browser-based interface allows students to run experiments, visualise data and draw evidence-based conclusions, while gamification elements reward efficient identification of causal components. The design supports inclusive use by enabling participation independent of location and allowing adaptation to different learning needs.
A first comparative study with mechanical engineering students indicates that the virtual training substantially reduces time and operator-induced variation, while maintaining self-reported learning outcomes and motivation. The primary contribution of this work is a transparent, openly available methodological tool for teaching systematic component swap, complemented by preliminary evidence of its usability and perceived educational value in engineering education.

Keywords: Virtual simulation, web-based training, gamification, inclusive learning, accessibility, data simulation, component swap, problem-solving

1 INTRODUCTION
Effective problem-solving relies on the systematic use of appropriate methodologies. Training in these methods is essential for both design and production engineers [1]. The Ishikawa and 5-Whys methods are commonly used in root cause analysis, but practical approaches also play an important role [2]. One of the most effective methods for isolating a failure in assemblies is to systematically swap components between a functioning and a non-functioning product [3][4]. This approach, also known as Shainin's 'component search' [5], is firmly established in industrial problem-solving processes and is therefore an important element of many problem-solving training programmes [6][7][8]. This is particularly relevant for design and development engineers, who must systematically analyse the impact of design choices on product quality characteristics. The component swap method is taught in quality management classes for mechanical engineering students at the DHBW Cooperative State University Ravensburg.
State-of-the-art training in quality management methods is characterised by practical case studies, business simulations and integration into holistic frameworks such as Six Sigma or 8D [9]. In education, catapults (see Figure 1) are often used as training aids, offering a process that enhances understanding [10]. Catapults serve as experimental objects that generate data with natural variation. They are easy to understand, have an intuitive functionality and can be easily adjusted to new conditions. This allows learners to analyse statistical relationships and investigate the influence of various components on relevant quality characteristics.
Such trainings sessions are effective because they combine technical and soft-skill development, immerse learners in realistic scenarios and foster interpersonal competencies needed for process improvement. On the other hand, catapult-based training faces several limitations, including high

resource requirements and limited scalability. Additional drawbacks include unwanted process and hardware variation, potential safety risks and barriers to participation due to logistics and accessibility. These factors reduce overall learning effectiveness and efficiency. In this context, training efficiency is understood as the relationship between the achieved learning objectives and the time and resources required to deliver the training.

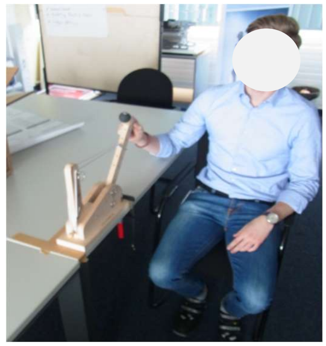

Figure 1. Catapult in problem-solving trainings

This paper addresses the following methodological research question: How can the training of a problem-solving process using the component swap method be improved by using a virtual simulation? To answer this question, a virtual catapult tool was developed and a preliminary evaluation comparing the virtual and physical setups was conducted. In doing so, the virtual catapult is used to explore how simulation can improve engineering education.

2 LITERATURE REVIEW

Virtual reality simulations and laboratories using digital twins are increasingly utilised in engineering education to provide students with hands-on experience in a safe, scalable environment [11][12]. Bai-Lin Li et al. [13] and Tisza et al. [14] showed that interactive virtual substation simulation training systems can significantly improve students' practical competence and engagement in engineering programmes. In practice, some virtual simulations related to quality training can be found, such as a moulding machine [15], a catapult [16] and a trebuchet [17]. These simulations focus on changing settings to optimise outcomes but not on identifying faulty components.

However, there is no virtual assembly tool for training the component swap method available. A review of the current scientific literature also reveals that implementations of component-swap training using virtual assemblies are not described or systematically evaluated.

This gap highlights an opportunity to contribute new insights into the design, application and instructional effectiveness of virtual catapult simulations for quality management education. Our work addresses this gap by introducing a parametric, web-based virtual catapult for evidence-based training in problem solving using component swap. The subsequent evaluation involves a comparison between training using a physical catapult and that using a virtual.

3 TRAINING USING PHYSICAL CATAPULTS

The current hands-on training for mechanical engineering students uses a scenario in which a customer has rejected two of three catapults due to projectile range being out of specification. The student group starts a structured problem-solving process following the 8D method. To verify the customer complaint, data is generated by firing the catapults and measuring flight distance. Unseen, the catapults have been manipulated e.g. weight of the projectile (ball) or length of the elastic band before usage. The results confirm the customer complaint (see Figure 2).

The problem-solving continues with applying a cause-effect diagram that lists potential causes such as wrong setup, ball weight or elastic band properties. These causes now need to be confirmed or rejected using problem-solving methods such as the component swap. Important prerequisites for component swap — such as the availability of functional and non-functional assemblies, ease of disassembly, and simple retesting are performed. Following the component swap approach [3] functional and non-functional assemblies (see example in Figure 2) are selected, disassembled and reassembled. If no change is observed, this indicates that the cause lies in the components rather than in the assembly process. Next, components are swapped pairwise (in Figure 2: catapult arm, projectile (ball) and elastic band) and assemblies are tested again. The graphical analysis confirms the causal component (in figure 2 elastic band). Further steps like the ‘5-Why’ method or ‘regression analysis’ are conducted to identify the underlying root cause. Finally, corrective actions are implemented and all catapults are successfully tested within defined specifications.

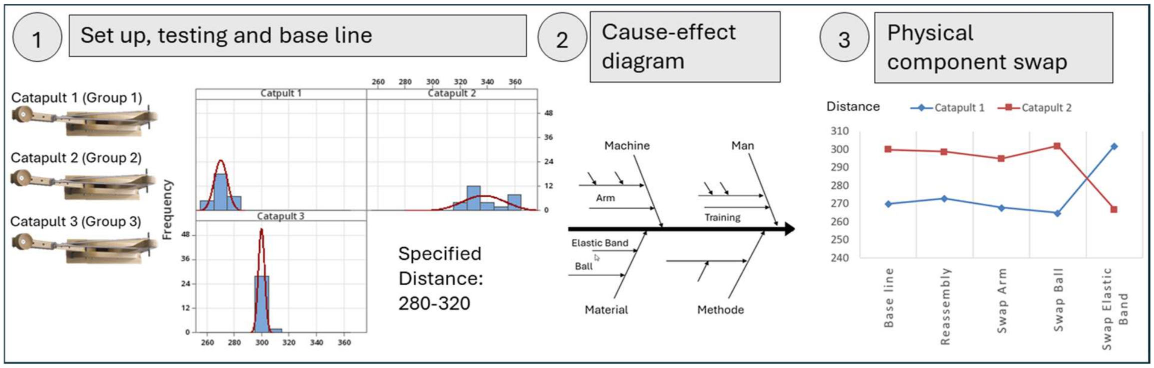

Figure 2. training with real catapults

While students appreciate the hands-on nature of the training, this approach exhibits several disadvantages:

- The generation of data for statistical analysis is very time-consuming, especially generating data after every component swap making the training less efficient.
- Training is restricted between nine to 15 students in physical presence, making it difficult to scale. Remote access or online training is not possible. Gamification is not well developed, as all students work in one shared problem-solving process, even when splitting up in teams.
- Flight distance is strongly affected by the students operating the catapult (around 20% compared to catapult-to-catapult variation). Together with additional factors such as wear of catapult components, training effectiveness is reduced.
- Difficulty of the problem – in terms of the number of manipulated components - is not adaptable to individual learning needs and may not fully address the needs of neurodivergent students.

These disadvantages highlight the need for simulation-based solutions that improve efficiency, scalability and accessibility while providing a safe, motivating environment for training the ‘component swap’ in engineering education, also under demanding course conditions, e.g. number of students, educational backgrounds, team compositions and dynamics.

4 VIRTUAL CATAPULTS: TRAINING CONCEPT AND BACKGROUND

The virtualisation must preserve the basic concept of the existing problem-solving scenario, using catapults as data generators. At the same time, it should add features such as gamification and multiple difficulty levels. The developed solution is a platform-independent simulation that realistically represents the physical behaviour of a catapult and virtually replaces the previous experimental setup. First, the new training concept is outlined, followed by technical details of the simulation.

4.1 Training concept and process

In the virtual catapult training, the scenario remains unchanged, but instead of firing physical catapults, students use the web interface *virtualcatapult-problemsolving.twie.website* to generate data. After selecting the difficulty of the problem, students explore the baseline by clicking “new measurement”, which generates a baseline dataset. Using a cause–effect diagram, potential root causes are developed and prioritised, similar to the current training. Suspicious components can then be swapped pairwise via drag-and-drop. With minimal additional time and effort, a new dataset is generated and can be analysed in the next step, confirming or rejecting the causal component (see Figure 3). Once the root cause is confirmed, further steps can be taken to solve the problem.

The scenario can be repeated as often as desired to increase learning success. In addition, the difficulty level can be gradually increased. To enhance motivation and competition, the number of components swapped and the resulting number of attempts are recorded and used as a gamification element.

4.2 Technical background and data generation

A central challenge in the technical implementation of the data simulation is not only to provide deterministic values, but also to reflect the variation of real processes. This is essential for quality management education, as students need to learn to distinguish between systematic and random variation.

Two main approaches for generating data were considered: engine-based and formula-based. While physical systems are well-suited for modelling collisions and complex interactions, they introduce unnecessary overhead and complexity for this specific use case. Instead, the focus was placed on the precise and reproducible calculation of projectile trajectories using defined input parameters. Direct mathematical modelling enables efficient control and high transparency of the simulation process, ensuring that results are both accurate and easily adjustable for training purposes.

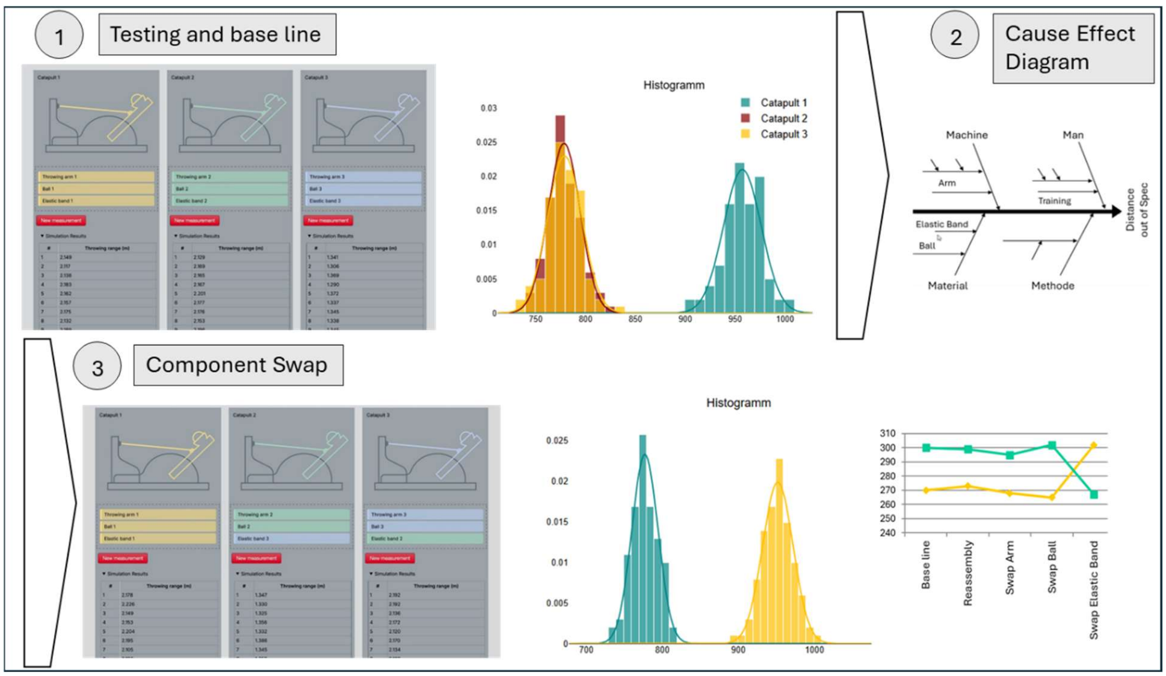

Figure 3. training with virtual catapults at a low difficulty level

Building on this formula-based modelling, the trajectory of the projectile is calculated using standard equations of projectile motion. The initial velocity is derived from the conservation of energy: the potential energy stored in the stretched rubber band is transformed into the kinetic rotational energy of the throwing arm. This initial velocity is then inserted into the equation for the x-coordinate, allowing the precise determination of the projectile's landing position and distance. Due to the fact that repeated application of the formula yields exactly the same distance, which does not reflect real-world conditions, variation is added to the simulation results. To achieve a realistic, natural variation, the 'Box–Muller' transformation was implemented. This method transforms two uniformly distributed random variables into normally distributed variables [18].

This enables the simulation of realistic measurement noise around the calculated ideal values, which was successfully validated by histogram analyses. The difficulty level is implemented by changing the number of causal components and the amount of variation in the dataset.

For intuitive usability, the web application utilises responsive design principles. A CSS grid layout ensures usability across devices, including desktops, tablets and smartphones. The user interface is organised into configuration areas for selecting difficulty levels and output areas where the generated measurement series are visualised in tabular form. This structure provides the technical foundation for digitally replicating real training scenarios in quality management. The application is implemented using standard web technologies like HTML, CSS and JavaScript. All code is provided as open source on the referenced homepage, supporting transparency and further development.

5 EVALUATIONS

To evaluate the virtual catapult simulation two training sessions were conducted, one with physical catapults (n=12 students) and one with virtual catapults (n=12 students), allowing a direct comparison. All students were second-year mechanical engineering students specialising in design and were randomly assigned to the two sessions. It was the first time they were challenged with the catapult problem. During both sessions, the same problem was stated and the problem-solving training followed 8D. Catapult operating time was recorded and after the session the students were asked in a survey about how they experienced the training. The results of the survey show that the perceived learning outcome was at a comparable level for both training formats (see Figure 4).

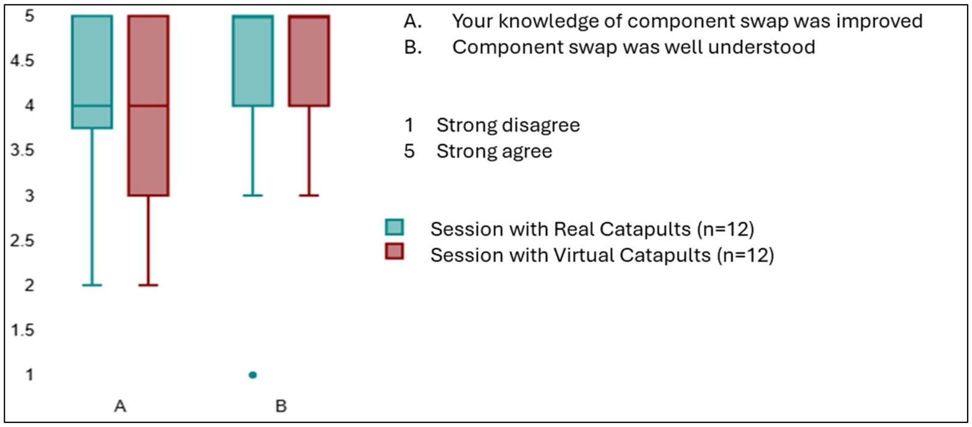

Figure 4. Boxplot of survey results from two training sessions

The evaluation of the virtual catapult demonstrated how the training of the component swap method is improved:

- Efficiency increased: Since no catapults were operated during the virtual simulation more than one hour of the five hours total training time was saved (20%).
- Training is scalable to larger groups, enables remote participation and improves accessibility. Gamification is supported, as students report their number of attempts.
- Flight distance is no longer affected by physical operation, making the effects of the components easier to understand.
- The difficulty of the problem can now be adjusted in each run, and the scenario can thus be adapted to individual learning needs.

Due to the small sample size, these findings are considered preliminary. Nevertheless, they provide valuable insights for further development and larger-scale studies.

6 CONCLUSION AND OUTLOOK

This paper introduced a web-based virtual catapult simulation developed to train the ‘component swap’ method as part of structured problem-solving in quality management. Building on the limitations of hands-on training sessions with physical catapults, the virtual approach provides an easily accessible environment that retains the core didactic strengths of the physical scenario while improving efficiency, scalability and flexibility. The simulation is accessible via *virtualcatapult-problemsolving.twie.website*, and the code is provided as open source, supporting transparency, reuse and further development by the community. An initial pilot evaluation with students showed reduced training time, removal of operator-induced variation and high levels of motivation through gamification. However, the shorter duration of the simulation meets the learning outcomes and competencies as in the cohort with physical training.

Future work will focus on a more systematic evaluation with larger and more diverse student groups to quantitatively assess learning outcomes, transfer effects and long-term retention compared to traditional training. As a methodological extension, additional quality tools should be integrated. For example, using the simulation to conduct a prior Design FMEA or to develop Poka-Yoke solutions could provide substantial added value, especially for design students, and would represent an interesting extension of the concept. The technical development of the simulation should be expanded to include advanced features such as adjustable experiment settings for comprehensive training in quality management methods, including Design of Experiments (DOE). Further enhancements could encompass additional error sources such as incorrect assembly, incorrect set-up and environmental influences. Finally, integration into blended learning concepts and remote lab settings will be explored to further strengthen the role of virtual assemblies and the 'component swap' method across different application domains in evidence-based engineering education.

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