FUNCTIONAL ANALYSIS IN PHYSICAL AND VIRTUAL REALITY (VR) ENVIRONMENTS – A COMPARATIVE STUDY

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ABSTRACT

Product development is time-consuming and cost-intensive. Part of the costs can be attributed to physical tests. Therefore, new methods are being researched to save resources. One upcoming area that becomes important for the industry is Virtual Reality (VR) technology.

In the state of research studies have already compared VR with methods such as CAD visualizations. However, there is a need for research regarding the comparison to physical models.

Therefore, a comparative study between a physical system and a VR system is evaluated in terms of functional analysis. The study task was to analyze the mechanism of a lawn sprinkler. For evaluation, a function explanation in a final interview was used.

Although more different representations were possible with VR, there was no general improvement. This could be because movements were more difficult to visualize and recognize. The VR application is very suitable if you mainly have to look at systems that are difficult to view in reality. For example, some physical systems may be challenging to see in operation or may not allow a physical cut, so VR can be a solution. The advantages of physical systems can be in using other impressions, such as a feeling of certain forces.

Keywords: Virtual reality, Design engineering, Design cognition, Human behaviour in design

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Cite this article: Steinhauser, N., Zimmerer, C., Grauberger, P., Nelius, T., Matthiesen, S. (2023) 'Functional Analysis in Physical and Virtual Reality (VR) Environments – A Comparative Study', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.202

1 INTRODUCTION

Product development is time-consuming and cost-intensive. Here, a part of the costs can be attributed to physical tests. This calls to find new methods for virtual testing to save resources. Already proven virtual testing methods, such as Computer-Aided-Testing (CAT), have shown that they can reduce testing costs. Companies are taking advantage of Computer-Aided-Engineering (CAE) to complete the development phase in shorter cycles and at a lower cost. Physical prototypes are being pushed back for these cost reasons. (Tahera, 2014)

These advantages of common CAT support the assumption of investigating novel processes for their suitability. Virtual Reality (VR) technology can represent a new possibility in this context. There, computer-generated 3D environments are created and used interactively (Orsolits and Lackner, 2020, p. 185). This creates a unique user experience in which the person is immersed in the virtual environment and shielded from the physical environment (Lang and Müller, 2020, p. 90). The virtual simulation thereby decides how close to reality the viewer perceives the VR environment. It is conceivable that VR technology can assist in the development process by providing realistic 3D visualization of models, therefore it is necessary to investigate this topic. Following this, the comparison of VR technology to verified but expensive physical models has not yet been sufficiently explored.

1.1 Background of existing VR studies

In the state of research, there are already some studies that deal with the use of VR technology. There are contradictory findings regarding the suitability of VR technology depending on different use cases.

A VR study by Wolfartsberger (2019) shows that participants with VR visualizations develop a slightly better understanding of the system and identify slightly more design-related issues than participants on a CAD model. In the study, 3D models were examined concerning predefined weak points and defects. Here, the participants were able to identify 21 design-related issues in VR and 18 in the CAD program Creo View (Wolfartsberger, 2019). In contrast, after a conducted study Barkokebas *et al.* (2019) came to the conclusion that VR training methods perform slightly worse than traditional learning methods. In this first study, it was not yet possible to find out what factors this might be based on. Among other things, the study dealt with the steps of assembling and disassembling components. One group was trained by reading an instruction manual and the other group in the VR training environment (Barkokebas *et al.*, 2019).

Despite this partly unclear data situation as to how well VR can now support, a general emerging finding can be identified in the literature. According to this, participants are mostly positively inclined towards VR use and suspect that VR could support in design review, as found for example by Aromaa (2017). The presented studies in the literature highlight the problem of the not yet clearly categorized benefits of VR, which may vary depending on the study. Partly VR is better, partly the other comparison group is better. However, the individual studies from the literature indicate a promising approach, which needs to be further investigated. A Key aspect is the comparison of VR to already established working methods, such as CAD viewing or traditional learning methods such as reading an instruction manual.

1.2 Functional analysis

The previous chapter already emphasizes the need for further studies that explore the benefits and risks of VR use in the technical environment. It is important under which aspects the VR use is examined and evaluated. It is central to enable people to understand a system in order to develop a novel product from this knowledge. In doing so, this premise ties into Eckert *et al.* (2012) finding that the analysis of technical systems is of central importance. For Eckert *et al.* (2012), functional analysis on technical systems is important because designers develop an understanding of the system from it. It is central to identify the positive and negative system properties as well as to find out which problems arise from them (Eckert *et al.*, 2012). In doing so, functional analysis involves breaking down the system into individual functions that are easier to understand, and identifying these functions is a core problem (Booth *et al.*, 2015).

The design review used in Wolfartsberger (2019) study shares a similar goal with functional analysis, namely to examine a shape to identify potential problems. Therefore, including this mentioned study

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makes sense. In addition, a design review includes even more approaches than a functional analysis, such as a larger design process with defined milestones (Wolfartsberger, 2019).

In summary, there is currently still the problem to keep the number of physical prototypes for functional analysis low even if it works very well. Keeping the number of physical prototypes low saves companies´ costs (Tahera *et al.*, 2014).

1.3 Aims

In order to examine VR technology in more detail, a study was carried out for this paper. The goal was to evaluate and compare the two studies that have been conducted. A study on a physical system was compared with a study on a VR system. From this, conclusions were drawn about how well systems can be understood in VR. This allows statements to be made about system understanding and is therefore of central importance for the development process. In addition, the study comparison explores the benefits of VR technology and identifies the potential and risks of VR use. Thereby, the study focuses on the investigation of the extent to which VR use is possible in the functional analysis of technical systems. The literature already contains studies (cf. Chapter 1.1) in which approaches similar to those described here are pursued. However, there is a need for research concerning the comparison to physical models presented at the beginning. Therefore, this paper deals with a comparative comparison of VR and physical models and deals with functional analysis in VR, since the identification of functions of technical systems in VR has not yet been investigated.

From the problem presented here, the research question of this paper was derived:

> What are the potentials and risks of using VR for functional analysis compared to functional analysis on a physical system?

2 MATERIALS AND METHODS

The following study design was used to test the functional analysis in VR on a technical system. The functional analysis of a lawn sprinkler in physical and in VR was compared in a participant study. Similarities and differences in the approach of the studies are explained below. The study design was adopted from Matthiesen *et al.* (2017).

2.1 Participants

Students were invited to participate in the study with the physical system or the study with the VR system. The sample consisted of 13 participants in the group with the physical system and 9 participants in the group with the VR system. The two experimental groups were selected according to an engineering course. The experimental group with the physical system consisted of mechanical engineering students, composed of two females and 11 males. In this group, the average age was 23.5 with a standard deviation of 2.0 years. The experimental group in the VR environment consisted of two females and seven males, composed of four mechanical engineering students, four mechatronics students, and one industrial engineering student. Their average age was 22.7 years with a standard deviation of 1.2 years.

2.2 Study and experiment setup

This section provides an overview of the implementation of the study environment and task. The participants' study task was to analyze the operation of the pivoting mechanism of a lawn sprinkler to explain the overall system. The lawn sprinkler system has been found to be a suitable system to study designers in previous research (Matthiesen *et al.*, 2017).

The system has the main function of distributing water evenly. In doing so, the lawn sprinkler can be subdivided into individual sub-functions (SF) following the force flow of the water. These sub-functions were used for the evaluation in the results section and helped to explain the operation of the alternating mechanism. The water inflow (SF1) occurs via a garden hose connection at the end of the housing. The incoming water enters the turbine chamber through an opening (SF2). The flow velocity of the water is converted into a rotary motion in the turbine wheel (SF3). A subsequent 1743:1 reduction gear (SF4) causes a slower rotation of the lawn sprinkler (Matthiesen *et al.*, 2017). To realize the actual pivoting motion, a toggle switch in combination with adjusting disks (SF5) reverses the direction of rotation of the turbine wheel and consequently of the entire lawn sprinkler. In detail, the toggle switch is connected to a rocker via a spring and swings over the spring Rocker (SF6). This

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closes one of two openings (SF7) depending on the position of the toggle switch. The water-carrying opening, which changes per cycle, causes the aforementioned change in the direction of rotation of the turbine (SF8).

The lawn sprinkler system was available to the participants as shown in Figure 1. The first row shows the physical system and row two presents the VR system. The main system components of each study are compared in the corresponding columns.

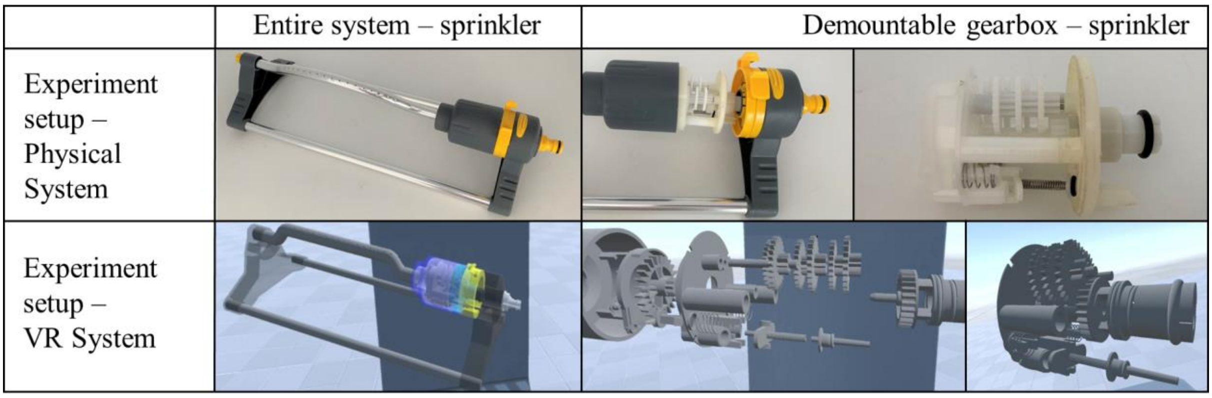

Figure 1. Study environment on the physical system and on the VR system.

2.2.1 Study on the physical system

In the study with the physical system, the participants were provided with the entire system as an assembled commercial lawn sprinkler. A prepared specimen was also used, which was supplemented with a viewing window on the gear chamber. The gearbox and its overall position in the system are shown in Figure 1.

2.2.2 Study in the VR environment

The VR study includes the equivalent lawn sprinkler system based on its CAD model. The VR study group got this system in a VR environment.

In the first step, the CAD model was converted into a .fbx format and then loaded into the Unity game engine, which was used to develop the VR environment. The VR hardware used was the HTC VIVE Head-Mounted-Display (HMD). The VR content could be grasped and moved spatially using a VR controller.

The participants were visualized the VR system as an assembled complete system with a transparent housing part and a gear unit (cf. Figure 1. Second row). In addition, the changing mechanism was shown as a disassembled system. Regarding the freedom of movement, the VR models differed from the physical system in that the depicted components could be moved as components, but the interaction of the individual components was not animated. For example, the toggle switch movement with the swivel movement of the rocker or the gear wheel rotation was not possible. The component size was scaled larger because of the resolution in VR. Otherwise, the component details could not be seen to the same extent compared to the physical system.

2.3 Experimental procedure

Figure 2 illustrates the study setup in the first row for the physical system and in row two for the VR system. The participants were guided through the study during the following steps.

During the study implementation, care was taken to ensure the highest possible comparability, on the one hand by means of a flowchart that ensured a comparable study procedure for each participant and, on the other hand, by means of a PowerPoint presentation that contained all necessary introductory information. The mentioned study design was adopted from Matthiesen *et al.* (2017). This study design has already been successfully applied several times (Matthiesen and Nelius, 2018; Zimmerer *et al.*, 2021). The PowerPoint presentation contained, among other things, a system briefing on the lawn sprinkler in order to set the participants on an equivalent prior system knowledge and not task-specific basics e.g., of controller handling in VR.

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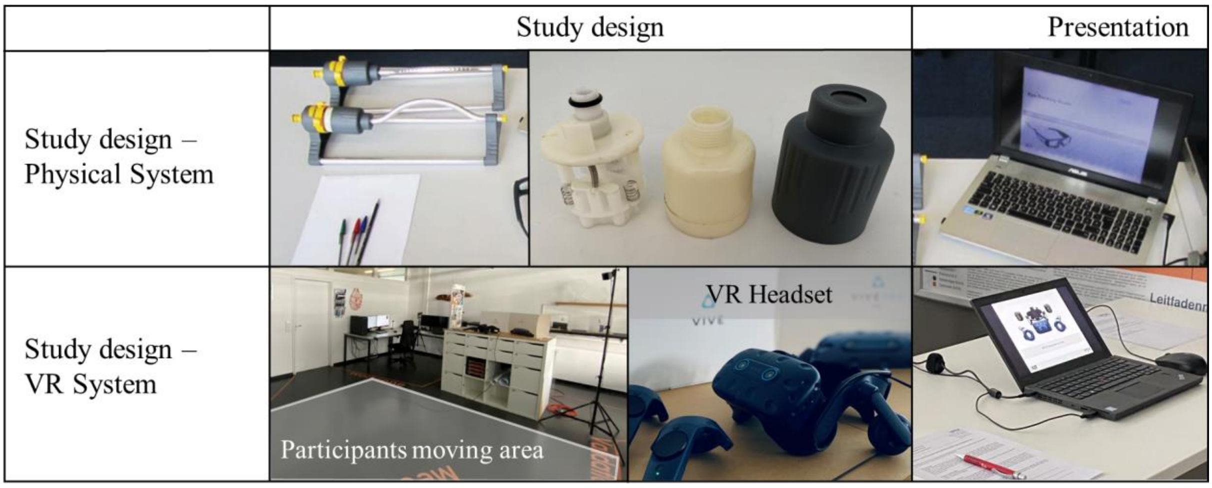

Figure 2. Overview of the study design. The prepared physical lawn sprinkler was used by the study group on the physical system. The HTC VIVE hardware and controller was used by the VR study group. The PowerPoint presentation contains all necessary introductory information for the participants.

2.3.1 Study on the physical system

The execution of the study with the physical system (cf. Figure 2. First row) can be divided into the following five steps.

1. Welcoming the participant, PowerPoint presentation with system introduction and briefing on the task (cf. Figure 2. First row right)
2. Handing over the lawn sprinkler models for the task processing (cf. Figure 1. First row left).
3. After the participant completed the system analysis while verbalizing his thoughts with concurrent think-aloud, a brief function explanation was given in a final interview. Through the use of the concurrent think-aloud method, participants were instructed to verbalize their thoughts, primarily to represent function-level information (Ruckpaul *et al.*, 2015).
4. The system was removed and a questionnaire regarding system understanding issues was filled out by the participant.
5. The experimental procedure was terminated and the room camera recordings and questionnaire responses were saved.

2.3.2 Study in the VR environment

The execution of the study with the VR system was carried out similarly to the physical system in five steps as in chapter 2.3.1. Therefore, only differences in the execution of the experiment compared to the physical system are explained below.

1. In addition, the participants were given an introduction to the VR HMD and the controller control.
   The VR HMD was placed on the participants´ heads and the controller controls were explained in a VR demo environment.
2. The lawn sprinkler model was not available to the participants as a physical model, but as a virtual model (cf. Figure 1. Second row).
3. Step 3-5: this was identical to the physical system.

2.4 Data collection and evaluation

The study implementation and results of the study on the physical system are based on a study conducted at the Institute for Product Development (IPEK) of the Karlsruhe Institute of Technology (KIT). The study on the VR system collected further data, for example, performance on sub-functions, for later evaluation and study comparison. The scheme for evaluating the sub-functions was first developed during the study conducted on the physical system at IPEK.
In both studies qualitative data collection methods were used for data collection. The most important one used for the evaluation of the study was the brief function explanations given in a final interview. This explanation was given by each participant at the end of each study session. In doing so, the

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participant described the function of the lawn sprinkler in detail. From this, qualitative data could be collected for the individual participant. With a questionnaire following the task processing, further information on the understanding of the system could be collected. This allowed a detailed follow-up of the collected data from the participants. In the process of the evaluation, the qualitative answers to the sub-functions were evaluated across all participants and quantified by the number of times they were mentioned. In the results section this quantification was necessary to identify overall tendencies for the understanding of sub-functions across all participants. For a representative comparison of the participants in the results section, the lawn sprinkler system was divided into sub-functions and evaluated with a point model (SF understood = 1 point; SF not understood = 0 points). The brief function explanation at the end of each study session was used to assess whether a sub-function was understood or not. The sub-functions have already been presented in the methods section 2.2 and are also listed in the results section Figure 3. Following the evaluation, a comparison of the two studies took place.
For the data analysis, there are also two independent samples, composed of the study on the physical system and the study on the VR system. The number of understood sub-functions can be ordinally scaled. These conditions fulfill the requirements to apply the statistical Mann-Whitney U test. For the evaluation, the dependent test variable and the independent grouping variable can be defined. The test variable defines the number of sub-functions understood according to the respective participant and group membership. The grouping variable assigns the two independent samples of the study on the physical system and the VR system. The significance level was chosen to be 0.05.

3 RESULTS

The results section presents the results of the study on the physical system and the study that took place in the VR environment. For this purpose, the two studies were evaluated and compared with each other.
Table 1 gives an overview of the number of sub-functions understood, with an assignment to the respective participant. This information is listed for the study with the physical system and the study in the VR environment.

Table 1. Sum of understood sub-functions (SF) for each of the study group on the physical system (n = 13) and the study group in the VR environment (n = 9). A maximum of eight SF could be detected.

Participant Physical (PP) System	**PP1**	**PP2**	**PP3**	**PP4**	**PP5**	**PP6**	**PP7**	**PP8**	**PP9**	**PP10**	**PP11**	**PP12**	**PP13**
Sum of understood SF	8	8	8	8	2	8	2	4	8	1	8	8	2
Participant VR (PV) System	**PV1**	**PV2**	**PV3**	**PV4**	**PV5**	**PV6**	**PV7**	**PV8**	**PV9**				
Sum of understood SF	7	3	4	5	3	8	6	2	7				

The study with the physical system has an arithmetic mean of 5.77. The study in the VR environment has an arithmetic mean of 5.00. Looking at the arithmetic mean, the two studies show only a small difference of 0.77. The results of the two studies are shown in Table 1. Table 1 shows that most of the participants recognized either very many (8 out of 13 participants identified eight sub-functions) or few sub-functions (4 out of 13 participants identified at most two sub-functions) on the physical system. In the VR environment, according to the evaluation, more participants were in the middle range when considering the number of sub-functions recognized. Only one participant identified eight sub-functions and one participant identified a maximum of two sub-functions.

Figure 3 compares the number of recognized sub-functions between the study on the physical system and the study on the VR system, each evaluated for all participants. The division of the overall system

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into sub-functions is based on the functionality of the lawn sprinkler system presented in the study environment in chapter 2.2.

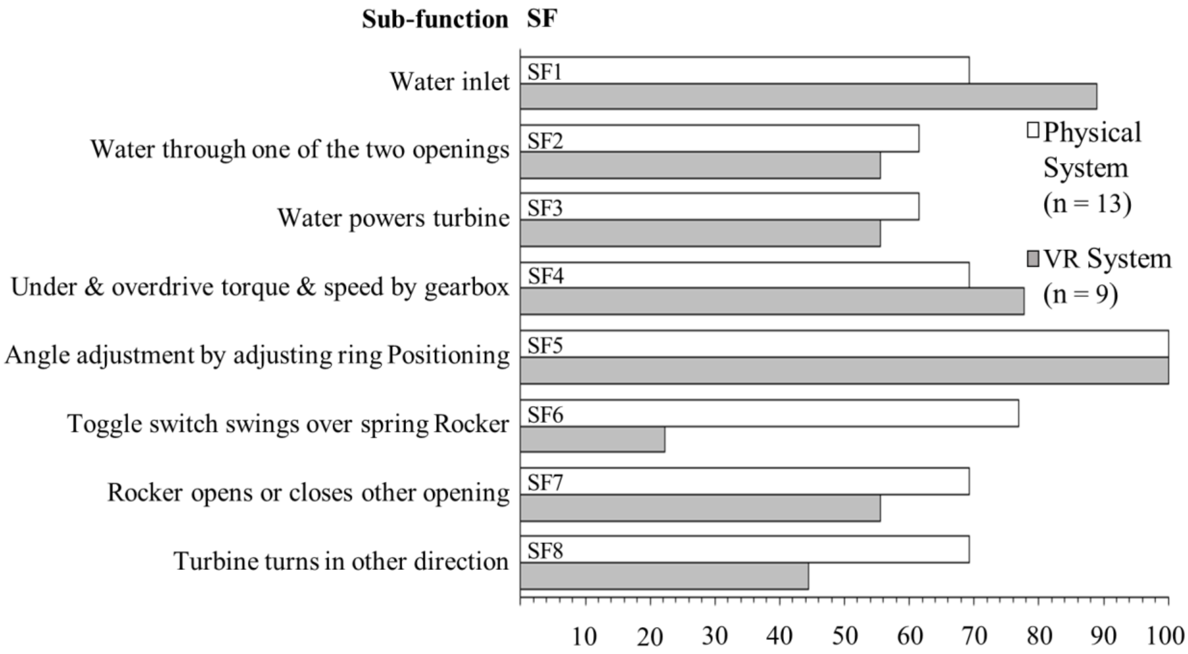

Figure 3. Proportion of participants who named sub-function correctly for the study on the physical system and the study on the VR system [in %].

The evaluation of the functional analysis shows a similar performance of the system understanding in VR compared to a physical system model. The identification of some sub-functions was better in VR, whereas other SF were better identified on the physical model.

- Looking more closely at the results in Figure 3, participants in the VR group recognized SF1 more often with 89 % (study on the physical system 69.23 %).
- Looking more closely at other sub-functions in Figure 3, there is no notable difference in the sub-functions SF2, SF3, SF4 and SF5. These were recognized with similar percentages both in the study on the physical system and in the VR study.
- Looking at SF7, the VR study performed slightly worse with 56 % compared to the physical system with 69.23 %. In addition, there was difficulty in detecting the change in rotation direction of the turbine (SF8) in the VR study (VR study 44 % and study on the physical system 69.23 %).
- There were clear difficulties with SF6 in the VR group, namely correctly interpreting the function of the spring on the rocker (VR study 22 % and study on the physical system 76.92 %).

To examine the central tendencies of the two sample groups, the Mann-Whitney U test was used. The null hypothesis here states that there is no difference in the central tendencies of the two study groups in the population. Analysis of the data revealed for the participants with the physical system (Mdn = 8) and the participants with the VR system (Mdn = 5) a value of $U(n_1 = 13, n_2 = 9) = 44$; $z = -1.007$; $p = 0.357$. Since the calculated exact significance of 0.357 is greater than 0.05, no significant difference between the samples can be demonstrated.

4 DISCUSSION

The discussion is divided thematically into two subchapters. The first subchapter deals with the potential offered by VR technology. The second subchapter discusses the risks that should be taken into account when using VR. In this context, the research question posed at the beginning, whether functional analysis in VR offers potential or is associated with risks compared to a functional analysis on a physical system, is discussed. The discussion comes to the conclusion that on the one hand, the use of VR offers some advantages, such as new possibilities regarding the immersive representation of 3D content compared to other computer simulations with a 2D display (cf. Chapter 4.1), but on the

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other hand also causes disadvantages, such as a loss of information in model animations (cf. Chapter 4.2).

4.1 Potentials of VR technology

The findings of this contribution support the findings of Booth *et al.* (2015), that individual functions are easier to examine. Here the system was divided into eight sub-functions, which could be analyzed correctly by a majority. During the analysis, the participants' statements could be assigned to these different sub-functions. This suggests that participants, when analyzing complex systems, subconsciously subdivide them into individual functions and sub-functions that are easier to understand. This happened subconsciously because no participant explicitly mentioned the division into single functions, but an assignment to single sub-functions was possible from the system descriptions. The sub-functions were recognized except for exceptional cases, which will be discussed in the next chapter.

Due to the possibility of a realistic simulation of the 3D components, the sub-functions SF2, SF3, SF4 and SF5 could be recognized in VR about the same number of times compared to a physical system. The computer-generated live simulation thereby replaces the physical environment with a purely simulated virtual world (Dörner *et al.*, 2019, p. 22). This forms the basis for the VR content and makes it possible to analyze individual sub-functions. Through this, the first sub-function, which describes the water inflow, could even be recognized better in VR. This may be due to the fact that in VR components can be enlarged and different viewing perspectives convey more information to the participants compared to the physical system.

Eckert *et al.* (2012) have shown that by analyzing a physical system, designers develop an understanding of the system. The results of the study comparison suggest that developing an understanding of a system through analysis is also possible in VR. This conclusion is supported by the similar performance of the previously mentioned sub-functions in both the study with the physical system and the study with the VR system.

The results section shows for the study on the physical system that several participants recognized either many or few sub-functions. This circumstance could not be assigned to any specific reason.

In the next chapter, however, reference is made to the problems that presumably led to the fact that several participants recognized individual sub-functions worse in VR. For example, one problem was the limited animation of some components.

In general, the study shows the potential of VR technology in the analysis of technical systems, since VR visualizations, for example, explosion views and disassembled model views (cf. Figure 1), can be easily implemented with the appropriate software. In reality, this is only possible by mostly complex prototyping for each newly selected system view. This leads to the finding that VR can be a useful new approach, especially for functional analysis in understanding design and not just consider VR in terms of its application to design.

As soon as the VR technology is compared not only with a physical model but with other computer simulations, further advantages arise. Models can be represented realistically in VR in a way that is not possible in any other technology. 3D representations and spatial movements possible in VR cannot be realized in any conventional computer simulations with 2D monitors. The intuitive grasping movements already allow natural interaction in the VR environment.

These advantages of VR technology can be used for certain applications. The VR application is therefore very suitable if you mainly have to look at systems. This is especially true for very small or very large physical systems that are difficult to view in reality. For example, some physical systems may be difficult to view in operation or may not allow a physical cut. VR can be a solution here.

4.2 Risks of VR technology

However, VR models also have disadvantages with regard to animations, since they always represent only an approximation of reality. The further the approximation deviates from reality, the more difficult it becomes to derive a specific component movement purely from the visualization. This turned out to be a possible cause of problems in the study with the VR system. In it, the spring rocker (SF6) and the gearwheel steps were not represented as movable. In contrast, these movements were possible in the study with the physical system. This allows the conclusion that due to this decisive interaction of the component movements, e.g. the SF6 could be better analyzed and understood in the physical study. This was a limitation in the VR environment compared to the physical experience.

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Despite this limitation in VR, comparison with the physical experience was still possible because the limitation did not affect participants´ overall functional understanding. Nevertheless, it is interesting to see how such limitations in reducing abstractions can affect the understanding of a particular sub-function.
Also problematic in VR in this context is the lack of haptic feedback from the part components. Although the interaction with the individual components can be represented, the actual resistance that occurs during a translational or rotational movement cannot. For example, the gear has resistance in reality. The gear wheel can be turned very smoothly on the turbine wheel side and therefore has a low resistance. On the other hand, there is a high resistance at the gear output and a rotation is only possible with difficulty. This important system information cannot yet be represented in VR. The only possibility might be to visualize the maximum force the participant would have to exert for a given rotation or movement.
In summary, haptic interactions are more difficult to reproduce in VR than in reality and physical resistance behavior cannot be implemented.
These aforementioned reasons likely resulted in the SF6, SF7, and SF8 being more difficult to recognize in VR compared to a physical system.
Physical systems prove to be advantageous here if you need other sensory impressions and the simple viewing of systems with basic interactions is not sufficient. These impressions can be e.g. the feeling of certain forces, the feeling of play or the hearing of certain system properties.

5 SUMMARY AND OUTLOOK

The results of this study were collected using a study comparison and 22 participants. A study with a physical lawn sprinkler system and a VR study using a virtual lawn sprinkler system were compared.
In the end, the study comparison could not show whether VR or a physical system is clearly better. Depending on the point of view, VR can be more suitable or the physical system. When the VR application can be useful or disadvantageous depends on the following factors.
The Advantages of VR can be the easy to realize animations, e.g. explosion views or disassembled system states. By choosing the right level of abstraction depending on the specific case, the animations created could be cost saving in VR. VR can be used for a fast and cost-effective realization of a CAD model to get first 3D experiences and analyses. This may allow costly prototypes to be pushed back in the design process and reduce the number of physical prototypes. The VR application is very suitable if you mainly have to look at systems. This is especially true for very small or very large physical systems that are difficult to view in reality. For example, some physical systems may be difficult to view in operation or may not allow a physical cut and therefore VR can be a solution.
In contrast, there are limitations in VR with regard to the sometimes too low animations of moving component parts. This leads to a conflict because a detailed animation of all moving parts in VR is still very complex. This is accompanied by the lack of possibility to reproduce the resistance behavior of component parts. For example, it is not possible to implement how the individual components behave when a certain force is applied. Thus, the user lacks information to analyze sub-functions. A physical system could score with this haptic feedback of the resistance behavior. In addition, the advantages of physical systems can be in the use of other sensory impressions, such as the feeling of certain forces, the feeling of play or the hearing of certain system properties.
Even in the state of research, it is not yet possible to determine a clear picture of the extent to which VR can be used. The study by Wolfartsberger (2019), in which the VR environment performed slightly better compared to a CAD model on a computer screen, differs from the study by Barkokebas *et al.* (2019), in which the VR training method performed slightly worse.
As a conclusion, it can be stated that VR use can be usefully employed for the functional analysis of technical systems. The aforementioned degree of abstraction of the VR animations plays a decisive role here. The better the real laws are approximated, the better the participants perceive the analysis possibilities. Here, this study comes to a similar conclusion that, according to Wolfartsberger (2019), VR is another tool and is currently not a substitute for conventional methods.
Further research is needed to examine the results in more detail as to why VR performed better on some sub-functions and physical environments on others. Here, it needs to be further investigated whether this is due to the aforementioned level of abstraction of the animations or involves other factors. This can be investigated on the one hand with different model animations in VR and on the

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other hand with further tools, e.g. eye tracking for data acquisition. According to Tahera (2014), other virtual testing methods already bring about a reduction in testing costs. Therefore, VR can also be a promising approach in this regard. Further research is therefore needed to determine whether or not VR can reduce the development costs of a product.

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