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A Decade of Virtual Reality in Product Development: A Literature Review of Effectiveness, Challenges, and Future Research

Ali Abughalia*, Carsten Stechert

Ostfalia University of Applied Sciences, Salzdahlumer Str 46/48, 38302 Wolfenbüttel, Germany

* Corresponding author. Tel.: +49-5331-939-44750; fax: 49-5331-939-44602. *E-mail address:* al.abughalia@ostfalia.de

Abstract

While VR shows promise in enhancing specific phases of product development according to some studies, its usefulness is questioned by others. This paper reviews the role of VR in the early phases of product development, focusing on three key areas: idea generation and initial model drawing, design review, and ergonomics studies. The review categorizes sources based on their support for or opposition to VR's effectiveness and explores future expectations for its role. A literature review from 2013 to 2023 was conducted, and potential areas for further research were identified.

Keywords: Virtual Reality; product development; idea generation; designreview; ergonomics; effectiveness

1. Introduction

The product development process is a systematic and structured approach aimed at designing, developing, and evaluating technical products [1]. This process is characterized by different phases, methods, tools, and techniques that are used to meet requirements and develop high quality products [2]. Virtual reality (VR) has emerged as a focal point in contemporary product development [3]. It has the potential to make the development process faster and more cost-effective, especially in the case of distributed product development [4].

Many publications have explored the use of VR and its advantages in product development. However, questions remain regarding where VR is most useful and which VR applications are best suited for specific tasks. One of VR’s key strengths in product development is its ability to visualize designs in a highly immersive and realistic manner. This capability is particularly beneficial for concept visualization as an alternative to physical prototyping, offering additional advantages such as cost-effectiveness. Therefore, this literature review focuses on three critical areas where VR has the potential to enhance product development: idea generation, design review, and ergonomics studies.

2. State of art

The product development process consists of a series of phases, starting with ideation, progressing through the conception phase, and culminating in the final product. Within these three main stages, several sub-processes occur, such as constructing a 3D design, conducting design reviews, and others.

VR provides a computer-generated 3D environment that enables a nearly realistic representation of products. Within this representation, the user can interact with the product in an immersive environment. The Term ‘immersive’ means that users are completely detached from their real surroundings, in contrast to ‘Augmented Reality (AR)’, which overlays virtual content onto the real world [5]. The most popular three VR systems are: Power wall, CAVE ,and HMD [6].

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2.1. Ideation process in product development

Product design is one of the most important step of product development. It consists of two approaches depending on the objective and the requirements of the product, such as creating a new product or modifying an existing one. In the case of developing a new product, it is necessary to generate a novel idea and then create an initial model to facilitate its visualization. This enables the team to evaluate the conceptual form and ascertain its compliance with the requisite criteria. This process is usually collaborative, with all team members contributing their ideas. The most persuasive design is typically the one that is the clearest and best fulfills the concept´s requirements. The ideation process, as defined by [7], is the process of gathering ideas for a potential solution to an identified problem and typically take place during brainstorming sessions. In these sessions, the ideas that have been generated are then represented using specific tools. For an extended period, designers have employed a range of tools to illustrate their ideas.

Goldschmidt [8] clarifies that illustrating an idea through sketching is important as it helps to give a near-final shape to concepts and aids in better understanding. This is because sketches created in the early phases of the ideation process often influence the final form of the product [9]. In this activity, it is necessary to compare the mediums used to sketch concepts. For a long time, drawing on paper with a pen has been the first and most popular tool for sketching. Recently, not far from paper, Tablets are now also used with a digital pen. However, both tools present some challenges, especially when it comes to drawing a 3D concept. Fleury et al. [10] clarify that when drawing a 3D object with a pen on paper or a tablet, more effort is needed to transform the idea into a 3D object. This includes considering aspects like the degree of shading and the relative distances of different dimensions to render the full 3D shape. The new sketching tool enables drawing in a virtual environment. In this virtual space, the user can freely draw using all planes of view and move around in all three dimensions to get a full bird's-eye view of the concept. It also allows users to change the stroke size and colours to meet all requirements.

2.2. Design review in product development

Once the product is designed, the corresponding requirements must be evaluated. In this phase, the team members engage in extensive discussions focused on the product specifications.

According to [11], a design review is defined as a set of activities that includes the interpretation and evaluation of a product based on previously established requirements, with the goal of identifying improvements to prepare the concept for the next stage of the design process. During the design review, the process of sharing knowledge and experience should not be confined to a single location. Many development teams work across distributed locations and require a medium that enables effective communication and understanding among team members. Typically, design reviews are conducted through CAD programs and other communication platforms. Nowadays, VR emerges as a medium for reviewing designs through an immersive experience. All team members can be involved and connected, regardless of their locations, as if they were in the same office.

VR as a communication medium in the design review plays a role in enhancing the understanding and interpretation of complex designs by providing immersive and interactive experiences [12]. This makes it easier for engineers to work with intricate designs without needing extensive experience or specific expertise. As a result, all team members operate as if they are on the same level of experience, which supports better knowledge exchange among team members. Moreover, participants using VR have been shown to detect errors more accurately and complete reviews faster than those using traditional CAD methods.

2.3. Ergonomics studies in product development

In product development, engineers required to consider not only the efficiency and quality of the product, but also to ensure that the product is safe and comfortable for users. This signifies that, during the design phase, the central focus is on human factors. This is due to the fact that users have specific limitations, including body measurements, strength, and range of movement. This principle of human-focused design is called ergonomics. According to [13], ergonomics is defined as “the scientific discipline concerned with understanding the interactions between people and other elements of a system, and the profession that applies theory, principles, data, and practices to the design of work systems, with the aim of optimizing human well-being and overall system performance”. The two main factors affecting ergonomics are often referred to the ‘user’ and the ‘work equipment’.

According to [14], the ‘user’ is defined as ‘a person or persons who responsible for installing, operating, setting up, maintaining, cleaning, repairing, or transporting machinery’. And the ‘work equipment’ is defined as ‘tools, including hardware and software, machinery, vehicles, equipment, furniture, facilities, and other equipment used in the work system.

The implementation of ergonomics with VR encompasses many areas of application, such as simulating workplaces to ensure they are safe for human use or designing machinery for new work environments before the physical environment is built. This approach helps to reduce repetitive tasks and enables design changes that improve safety by preventing injuries, particularly for workers in maintenance areas [15], which is especially useful for complex and hazardous machines, such as those in nuclear facilities. Another key aspect that ergonomics improves through VR is testing accessibility and human movement in some environments such as trains or airplanes, allowing engineers to analyse body mechanics and observe which tools and materials are easily accessible without causing strain.

When conducting ergonomic testing using VR, it is essential to consider the interactions between the user and the environment, tools, and activities [16]. Users must be able to navigate and manipulate the virtual environment in real time as avatars that accurately reflect their body dimensions in different postures (e.g., standing, leaning, lying down) and receive real-time information about their current position in space and the distance to specific components. Receiving feedback (haptic, acoustic, or visual) based on their actions enhances the realism of the interaction; for example, auditory cues may signal friction.

In addition, users need to be able to block or remove entire components or areas from the design (e.g., within large structures such as trains or airplanes) to facilitate access to desired areas or to test alternative scenarios. The tools utilized may include joining techniques such as welding, mechanical joints like bolting, and form-fit methods (e.g., press-fit, serrated, and wedge joints), along with support tools (e.g., cordless screwdrivers). Another important activity is representing the properties of each part, such as weight, material, and strength, as well as the interactions between materials, including friction, deformation, and elasticity, which should be taken into account to enhance the realism of the scene.

3. Procedure

In this review, a systematic methodology was applied to answer the question: 'Can current VR applications be integrated into product development, and what criteria should be considered when selecting and implementing VR applications?' This review focuses solely on immersive VR, excluding other VR-related technologies such as human modeling. The aim is to evaluate the role of VR in product development based on currently available applications, rather than assessing the applications themselves. Therefore, this review involves identifying and summarizing studies that meet the criteria necessary to answer the research question.

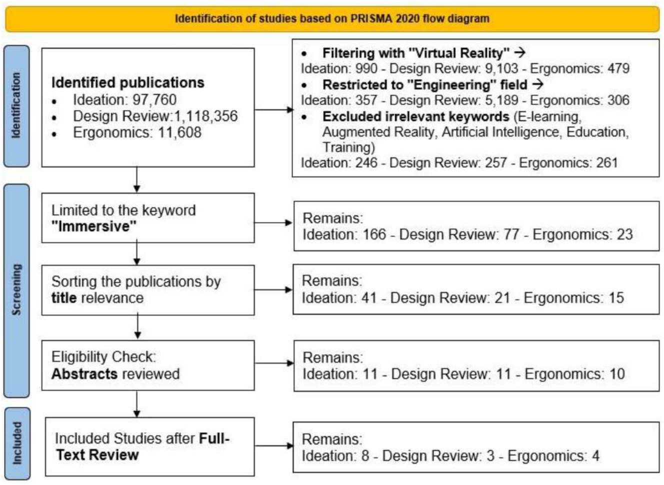

Figure 1 Process of sorting the literature review.

The results provide recommendations for implementing VR in product development, highlighting its strengths and limitations to support industry decision-making. Additionally, this review identifies future research directions, outlining areas that require further investigation and improvement within this field. The review was conducted using **Scopus** database for the research process. The review was limited to publications from 2013 to 2023, as the first comfortable headset system, the Oculus Rift, was developed in 2013. The review process is summarized in Figure 1 based on [30].

The review was structured into three main clusters: Ideation, Design Review, and Ergonomics. The search process was refined using specific keywords, Boolean operators, and exclusion criteria to ensure the selection of the most relevant studies.

The search was limited to "immersive" environments, filtered with "Virtual Reality", restricted to the "Engineering" field, and excluded irrelevant keywords such as "E-learning", "Augmented Reality", "Artificial Intelligence", "Education", and "Training" to ensure relevance to industrial use. The process involved systematic filtering through title and abstract screening to refine the selection.

For Ideation, the initial search retrieved 97,760 records. After applying the defined filters, 166 records remained. Title screening reduced this number to 41, followed by abstract screening, which further narrowed the selection to 11. Finally, 11 studies were included for detailed investigation.

For Design Review, the search initially retrieved 1,118,356 records. After filtering, 77 records remained. Title screening reduced this number to 21, and further abstract screening refined it to 11. Ultimately, 11 studies were selected for detailed investigation.

For Ergonomics, an initial 11,608 records were identified. After applying the search restrictions, 23 records remained. Through title screening, this was reduced to 15, followed by abstract screening, which narrowed the selection to 10. Ultimately, 10 studies were chosen for detailed investigation.

This structured methodology ensured a systematic selection of studies most relevant to product development in virtual reality environments, focusing on key areas of research.

4. Results

This section summarizes the results of the review according to the three previously considered themes.

4.1. Ideation process with VR

In this section, only eight relevant publications were found for the review.

In the first study [10], the aim was to investigate how a natural virtual environment affects the creativity of designers, particularly their ability to generate ideas in VR. In the study, each participant took 27 minutes to generate an idea. The author attributes the long time taken to generate an idea that the participants frequently changing colors, adjusting sizes, and teleporting within the scene, which suggests that these actions may enhance creativity.

The author in [17] studied how AI and VR affect the creativity of participants during brainstorming sessions aimed at generating ideas. The role of the AI was to replace the moderator in the session. However, particular interest lies in the conclusion that indicates VR, with its immersive capabilities, supports creativity, increases emotional engagement, and foster a sense of presence. The author goes on to explain that VR allows participants to focus on the problem and solve it more effectively through enhanced visualization and active interaction with the design.

In the study [18], the author examines the advantages of designing an aircraft cabin using VR and compares these advantages to using 2D and 3D design methods. A 2D sketch offers limited detail and flexibility, while a 3D model improves visualization but still requires effort to modify textures, materials, and lighting. VR enhances this process by allowing real-time interaction and adjustment within the model. Clients can 'walk through' the space and collaborate with designers to make instant changes, thereby streamlining the approval process. Beyond client communication, VR also serves as a powerful tool for quick sketches during brainstorming sessions. The author highlights that while VR technology offers benefits, it also has drawbacks, such as the need for costly equipment, user adaptation time, and potential health concerns such as nausea. In addition, users may feel uncomfortable being "blind" to their surroundings while others can still see them.

In the study [19], an experiment was conducted including five tasks to compare 2D paper-based sketching with 3D virtual sketching. These tasks explored different aspects of visual thinking such as visual transformation through mental image manipulation, visual synthesis by sketching shapes from verbal descriptions, visual spatial reasoning with interconnected 3D shapes, visual memory and comprehension through recalling shapes, and visual expression through unrestricted freehand sketching. The experiment concluded that VR sketching was innovative, valuable, and more natural than 3D CAD. However, the author clarifies that representing non-planar curves and surfaces was difficult both on paper and in immersive 3D sketching, and that sketching complex 3D models in VR remains as challenging as it is on paper.

The aim of the study [20] was to investigate how immersive technology affects creativity. Two environments were tested: VR, where participants appeared as avatars, and mixed reality (MR), where they could see each other in real life. Participants showed higher creativity in the VR more than in the MR. However, they found it harder to collaborate in VR due to the lack of facial expressions and natural reactions, which made communication feel less personal.

The study [21] set a task for participants to design a portable lamp using VR, followed by an evaluation to select and improve the best option. The results show that VR provides more information than traditional 2D sketches. By allowing users to view and interact with designs in real size, it facilitates modifications, speeds up the design process and enables earlier decision making.

In the study [22] , the authors investigated design ideation for car lighting using two cases: one using a game engine to visualize early exterior lighting concepts, and another using VR to visualize early interior lighting concepts. The focus is on the second case, where VR was investigated independently of the first case. In the VR case, the author tested its use for ideation and found the experience positive. VR allowed users to easily add or modify lighting sources and settings in real-time, facilitating easier exploration and design suggestions. The visualizations in VR were of high fidelity.

This study [15] is somewhat tangential to our review; although it is not suitable for the ideation process, it provides valuable information for the recommendations we need at the end of this review regarding the future use of VR. The aim of this study was to determine whether VR tools are useful and accurate for creating advanced freeform CAD models. Two case studies were conducted to explore the differences between modeling a 3D part, specifically a computer mouse, using CAD and VR. The results show that modeling in VR is faster and more intuitive but less accurate. Precision is crucial in mechanical engineering design, so it cannot be ignored here. Additionally, VR lacks certain features found in CAD, such as Boolean operations, which allow users to combine, subtract, or intersect basic geometric shapes.

4.2. Design reviews with VR

In this section, only three relevant publications were found for the review.

In the study [23], the authors investigated the differences between traditional CAD tools and immersive VR tools for 10 design reviews, focusing on the number of identified issues. According to their findings, more issues were detected using VR in larger models (e.g., wheelchair, weightlifting equipment, and baby stroller), while CAD was reported to identify more issues in smaller models (e.g., tricycle). However, the authors acknowledge the study’s limitations, as it only examined the number of identified issues without considering other performance aspects of design reviews. Additionally, they note that the range of designs reviewed was not broad enough to cover a wider range of complexity.

The study [24] investigated the effectiveness of different presentation methods (static images, animation, and image-based VR) in conveying conceptual design ideas. According to the authors, among 25 participants, VR was reported to be the most effective, followed by animation, although the results were not statistically significant. The study suggests that combining methods is more effective than using a single one, as VR presentations resulted in fewer questions and conveyed more information. The authors conclude that while combining methods is beneficial, VR alone is the most cost-effective option for conveying design ideas.

The study [25], examined two 3D models (power unit machines EVA1 and EVA2 with similar flaws) to compare the effectiveness of VR and CAD software in identifying design flaws. The study concluded that VR is a valuable addition to current design review methods, providing a more immersive, interactive experience that improves communication, collaboration, and speeds up the review process. However, the study also identified challenges, such as the need for more intuitive interactions, consideration of user perspectives, and further research in real-world settings.

4.3. Ergonomic studies with VR

In this section, only four relevant publications were found for the review.

The study [26] highlights the challenges of ergonomic design in industrial assembly and maintenance (IMA) for complex products such as satellite cabins. The authors propose a VR-based method to optimize ergonomic design by verifying two related ground maintenance plans before launch and assessing the feasibility of installing a support beam for worker comfort while minimizing risks related to human factors. They conclude that this VR method effectively enhances ergonomic design in IMA scenarios, improving time efficiency, accuracy, and modularity, and is applicable to various industrial contexts.

The study [27] presents a case study using a proposed methodology to evaluate the ergonomic design of two specific areas in a Maritime Patrol Aircraft (MPA): the console operator area and the observer window area. According to the study, problems were identified with screen visibility and control reachability in the console area, as well as visibility issues in the observer window area, leading to significant upper body strain. The authors report that the use of immersive VR enabled a comprehensive ergonomic analysis, revealing that the current design was uncomfortable and unusable for workers. They conclude that the methodology was effective for assessing these areas but emphasize that further research is needed to evaluate other parts of the MPA interior.

The study [28] investigates the use of virtual prototyping (VP) for human factors/ergonomics (HFE) assessment during the design phase. It compares augmented reality (AR) and virtual environments (VE)—with VE referring to the virtual space enabled by VR technology—in terms of their ability to support HFE evaluation. According to the study, a virtual model of a maintenance platform was used to evaluate tasks in the VE case. The authors report that VE was found to be more effective than AR for assessing visibility, accessibility, and tool use. Additionally, they highlight that factors such as fidelity, virtuality, and system dynamics influenced the suitability of virtual prototypes for HFE evaluation.

The study [29] presents a VR simulation environment for evaluating human-robot collaboration in an aircraft final assembly line. The simulator enables the investigation of different automation strategies, assessing productivity and ergonomics, with a focus on worker safety in confined spaces. The authors evaluated worker ergonomics, considering factors such as posture, reachability, and visibility of assembly parts. According to the study, the findings highlight the effectiveness of VR in process planning and evaluation, indicating that human-robot collaboration can improve worker ergonomics and reduce the risk of musculoskeletal disorders. The authors suggest that this VR simulator is a valuable tool for optimizing assembly scenarios and assisting engineers in decision-making.

5. Critical evaluation

This section investigates the strengths and limitations of implementing VR in product development based on the research question in chapter 3.

5.1. Strengths of VR in Product development

In ideation, VR enhances creativity by enabling users to generate numerous ideas during the brainstorming process. Additionally, it facilitates the creation of initial 3D concepts and improves their illustration, making it easier to communicate ideas and identify potential design issues.

In design review, VR improves the process by providing a more immersive and interactive experience, allowing for better visualization and understanding of complex designs. VR detects more issues in larger models, while CAD identifies more in smaller models. Furthermore, the effectiveness of VR in design review depend on the type and size of the product, as well as the users' level of experience such as stakeholders or external clients.

In ergonomics, VR assesses human safety risks and optimizes ergonomic tests, reducing the need for physical prototypes and improving worker comfort and productivity. VR is capable of evaluating human-machine interaction in the workplace, identifying potential ergonomic hazards and improving design outcomes.

5.2. Limitations of VR in Product development

Current VR tools may not be suitable for all phases or tasks in product development. Several factors limit their use, including integration into the current development process. Another limitation is precision, as VR may lack the accuracy required for certain tasks, such as modeling complex 3D parts, and its use is limited to generating initial 3D concepts with less precision. Furthermore, VR is not effective for existing products undergoing modifications (facelift). Additionally, the limited capabilities of VR tools mean they are not suitable for all phases of product development. An important challenge is the adoption process, where VR faces competition from other technologies, such as AR, which may compete for the same applications. Furthermore, the lack of standardization in VR technology and applications may hinder broader adoption.

SWOT Analysis		Internal Analysis	
		Strengths	Weaknesses
External Analysis	Opportunities	- Enhanced user Creativity. - Improved visualization and Communication. - Highly effective for large machines. - Ergonomic benefits and Safety. - Increased time savings.	- User resistance. - Cybersecurity concerns. - Increased efficiency in small machine. - Competition from other technologies(e.g. AR). - Integration costs & Equipment/License Price.
	Threats	- User experience. - Limited Standardisation. - Integration with CAD systems. - New Technologies with more Features. - Needed Training for new technology.	- Health concerns. - Limited precision. - Limited capabilities (not for all steps in product development) - Increased adoption in product development. - No improvements and less outcomes in process.

Figure 2 SWOT (strength, weaknesses, opportunities, threads) analysis.

In Figure 2, a SWOT matrix summarizes the strengths and weaknesses, along with the related opportunities and threats. It highlights five factors that could be either strengths or weaknesses, depending on the context of their impact. For example, for the factor 'user'; while VR enhances user creativity, it may also encounter acceptance challenges from some users. However, with proper training and familiarization, this user acceptance can be ensured. Nevertheless, health concerns, such as cyber sickness or eye strain, may pose challenges that cannot be fully overcome.

6. Future Work

In future research there is a need to create a VR tool that supports both 2D and 3D sketching, enables the creation of professional and accurate designs, and integrates seamlessly with CAD systems. Additionally, exploring the integration of VR with other technologies, such as AR, and AI, could lead to the development of more comprehensive and effective product development tools. Furthermore, investigating cybersecurity risks associated with VR technology is crucial, along with developing methods to protect sensitive design data and mitigate cyber threats. Furthermore, creating training materials will be essential to help designers, engineers, and other professionals effectively utilize VR tools.

Future research should focus on several key questions. One important aspect is the potential percentage reduction in rework when using VR in product development compared to traditional methods. Another area to explore is the extent to which integrating VR with CAD systems can reduce the number of design reviews and enhance collaboration. Additionally, research should examine how effectively VR-based ergonomic analysis can minimize workplace injuries and improve worker comfort in hazardous environments. Finally, it is crucial to investigate how reliance on physical prototypes can be reduced and how product testing and evaluation can be enhanced through VR-based virtual prototyping.

Answering these questions enables management to make informed decisions regarding resource allocation, technology adoption, and strategic planning in product development.

When deciding to implement VR in product development, managers also need to conduct a thorough analysis of their technology needs, taking several key factors into account. These include the type of task and scope of use, as different VR tools serve distinct purposes, such as sketching, creating designs directly in VR, or rendering finished CAD files for design review. Additionally, user experience is crucial, managers should identify whether the tools will be used by a development team with design and engineering skills or by external stakeholders needing to review designs. The size and type of the products being manufactured also influence the effectiveness of VR tools. Finally, assessing the budget and potential return on investment compared to current performance is essential for financial success.

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