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Optimisation of 3D models for visualisation in virtual reality systems

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Abstract. The relevance of the study is conditioned by the growing use of virtual reality in education, medicine, design and engineering systems, where traditional 3D models are often too resource-intensive for stable interactive reproduction. The purpose of the study was to identify and test the effectiveness of complex adaptation of digital objects to interactive spatial reproduction in conditions of limited hardware resources. The research methodology combined theoretical analysis with experimental testing in Unity 2022.3 on the Meta Quest 2 platform with performance and visual quality assessment. The results of the study showed that direct use of traditional 3D models in virtual reality is ineffective due to excessive load on hardware resources and instability of scene reproduction. It was established that the highest efficiency is provided by complex adaptation, which combines simplification of the polygonal grid, reduction of the volume of texture data, simplification of materials, application of detail levels, and stage optimisation. After adaptation, the number of polygons in the studied models decreased by 95-96%, and the volume of texture data – by 85-88%. In the test virtual environment, the average frame rate increased from 42 to 85 frames per second, which confirmed a significant increase in scene performance. However, the increase in performance was not accompanied by a critical loss of visual quality, since the overall shape of objects remained at the level of 98-99%, and the level of visual immersion remained high. The results of the study can be used by developers of virtual reality applications, computer graphics specialists, teachers, designers, and engineers to create training simulators, architectural visualisation, medical simulators, and technical virtual reality systems with increased performance and visual realism

Keywords: application of detail levels; simplification of the polygonal grid; interactivity; visualisation; level of visual immersion; frame rate

INTRODUCTION

The growing use of digital immersive technologies in education, cultural heritage, design, advertising, and visual communications has highlighted the challenge of effectively utilising 3D models in environments where high frame rates, interactivity and visual realism are all required simultaneously. For such systems, the geometric detail of the object itself is no longer enough, since without special adaptation, even a high-quality model can create an excessive load on the graphic subsystem, worsen the stability of scene reproduction, and reduce user comfort. That is why the use of three-dimensional modelling in computer graphics is associated not only with the creation of visually complex content, but also with its rational adaptation to the requirements of interactive immersive environments. In the scientific Ukrainian discourse, the topic of three-dimensional content was actively developed primarily in the pedagogical context. S. Lytvynova (2022) showed that students' readiness to use virtual reality (VR) in the educational process depended not only on access to digital tools, but also on the development of the ability to work with immersive content as a special type of learning environment. In the subsequent research, S. Lytvynova (2024) found that 3D content and 360-degree formats expanded the

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teacher's didactic capabilities, but their effectiveness directly depended on the quality of digital materials preparation and their compliance with practical educational tasks. A.S. Derkach & I.A. Tverdokhlib (2024), analysing the state of study of three-dimensional modelling in the Ukrainian school, noted that this area has already gone beyond the narrow technical specialisation and acquired the value of basic digital competence related to engineering, medicine, manufacturing, and design. S.O. Semerikov *et al*. (2024) expanded on this context by proposing a training methodology for WebAR development incorporating machine learning models, which highlighted the increasing complexity of modern immersive educational environments. P.P. Nechypurenko *et al*. (2023) demonstrated the practical effectiveness of a virtual chemical laboratory based on augmented reality to support students' learning and research activities. Together, these studies confirmed the high relevance of three-dimensional and immersive environments in education, but did not provide a specific explanation of how detailed digital models should be adapted for stable operation in VR.

A similar trend was observed in papers devoted to digital spatial reconstructions, virtual expositions, and visual communications. I. Tytarenko *et al*. (2023) proved that digital instruments allowed reproducing historical environments with a high level of spatial accuracy, and three-dimensional modelling could act not only as a means of visualisation, but also as a tool for research reconstruction. N. Dumanskyi & N. Vovk (2025) stressed that virtual and augmented reality technologies have strengthened the possibilities of preserving, reproducing and popularising the cultural heritage of Ukraine, especially in the face of military threats. M. Chernikov *et al*. (2025), analysing multimedia virtual exhibition spaces, showed that not only technical characteristics were crucial for the digital environment, but also aesthetic integrity, navigation convenience, and emotional immersion of the user. M.S. Strelchuk (2025) showed that three-dimensional modelling in advertising products was used as one of the leading means of forming a visual image, and the combination of 3D graphics with VR, augmented reality (AR) technologies, animation, and gamification increased the emotional involvement of the audience. All these studies convincingly substantiated the value of three-dimensional content for education, culture, design, and communication, but the issue of its quantitatively verified optimisation for VR scenes remained insufficiently disclosed.

Another important area was formed at the intersection of three-dimensional scenes, digital interaction, and new ways of presenting spatial information. R. Partsey *et al*. (2025) found that text annotations expand the ability to interpret three-dimensional scenes and enhance their semantic clarity in complex digital environments. This indicated a growing interest not only in creating 3D objects, but also in their structural organisation and adaptation to new interaction formats. Together with above research papers, this pointed to a significant gap: despite a significant interest in the educational, cultural, design, and communication potential of three-dimensional content, Ukrainian studies did not pay enough attention to the complex adaptation of models specifically for interactive VR, where frame rate, stage stability, textural rationality, and the preservation of visual realism became critical.

Despite the scientific significance of the considered studies, they do not sufficiently cover the issues of complex adaptation of three-dimensional models to an interactive environment VR, in particular, a quantitatively verified combination of geometric, textural, material, and scene optimisation to ensure high performance, rendering stability and the preservation of visual realism simultaneously. The purpose of this study was to substantiate and experimentally test the effectiveness of complex adaptation of 3D models for interactive reproduction in a VR environment under conditions of limited hardware resources. The objectives of the study were: to systematise the main approaches to optimising 3D models for VR environments; to experimentally verify the impact of comprehensive model adaptation on performance, rendering stability, rendering latency and hardware load within a VR scene; to assess the preservation of the visual fidelity of the optimised models in terms of geometric similarity, texture rendering quality, perception of detail, and the level of visual immersion.

MATERIALS AND METHODS

The study was theoretical and empirical in nature and combined the analysis of scientific sources with practical experimental testing of 3D models in the VR environment. At the first stage of the study, the material of theoretical analysis involved the research papers by S. Sukaridhoto *et al*. (2023), A. Geris *et al*. (2024), R. Grande *et al*. (2024), X. Hu *et al*. (2025), G. Papaioannou *et al*. (2025), Y. Wang *et al*. (2025), and H. Zhang & C. Peng (2026), which considered contemporary approaches to optimising 3D content for the VR environment. The choice of these sources was determined by the fact that they covered the main areas of adaptation relevant for this study, namely, simplification of the polygonal grid, optimisation of textures and materials, use of detail levels, organisation of rendering, and stage optimisation. Based on these studies, the theoretical basis of experimental design was established. Within this stage, approaches to geometric optimisation, reducing texture load, simplifying materials and visual effects, applying levels of detail, and stage optimisation were summarised. The theoretical analysis became the basis for constructing an experimental design and selecting technical parameters for further testing the effectiveness of adapting 3D models.

The empirical part of the study was performed in the Unity 2022.3 environment with integration under the standalone VR platform Meta Quest 2. The original models were created in Blender 3.6 in a highly polygonal format with maximum geometric detail and complex physically correct textures, and then imported into Unity without prior optimisation. Further adaptation was carried out using the built-in tools Mesh Optimiser, Texture Compression, Automatic Level of Detail (LOD) Generator, and Asset Store plugins focused on the requirements of autonomous VR systems. The research material consisted of four basic 3D models representing typical objects of virtual scenes: the chair model as a static interior element, the tree model as a landscape object, the building facade model as an architectural element, and the anthropomorphic character model as a dynamic object. This selection allowed covering various types of geometric complexity, texture saturation, and functional purpose of objects in a VR environment. At the first stage, all models were analysed in their original state. At the second stage, a complex adaptation was applied to them, which included simplifying the polygonal grid, creating 3-4 levels of detail, combining textures, using Adaptive Scalable Texture Compression (ASTC), replacing some highly detailed colour textures with normal maps and roughness maps, and simplifying materials and programmes for calculating visual effects.

To assess the impact of adaptation on performance, a test scene was created that contained 120 objects as a combination of four basic models and reproduced a loaded VR environment of a mixed "interior + landscape" type. The measurements were performed in standalone VR mode on Meta Quest 2 over 300-second sessions. Tests were conducted on a standalone Meta Quest 2 VR helmet in offline mode, without connecting to a personal computer to render the scene. The device's hardware platform included a Qualcomm Snapdragon XR2 system-on-chip, 6 GB of RAM, and a display with a resolution of 1832×1920 pixels per eye, and support for refresh rates of 60, 72, 80, 90 and 120 Hz. The experiment used a 72 Hz mode because it met the minimum target level of stable VR scene playback for a standalone device. The internal memory of the test device was 128 GB. During the experiment, third-party background applications were closed, and scenes were launched without streaming images from a personal computer. Graphics and CPU load, memory usage, frame rate, and latency were recorded using Unity Profiler and Oculus Performance Metrics. This configuration allowed evaluating the effectiveness of the models' adaptation specifically for a resource-constrained standalone VR platform. The data collection tools were Unity Profiler and Oculus Performance Metrics. Descriptive statistics were used to quantify the stability of scene reproduction, in particular, the average Frame Per Second (FPS) rate and the sample standard deviation of FPS values. The standard deviation (SD) was calculated based on a sequence of frame rate values recorded during each 300-second test session using Unity Profiler and Oculus Performance Metrics, using the equation (1):

$$SD = \sqrt{\frac{\sum_{i-1}^{n}(FPS_i - FPS)^2}{n-1}}, \tag{1}$$

where FPS_i – frame rate value in the i-th time frame; FPS – average frame rate value per session; n – number of recorded values. A lower standard deviation value was interpreted as higher rendering stability and lower variability in VR scene performance. The analysis covered the average frame rate, the minimum frame rate at the lowest values of 1%, graphics and CPU load, video memory usage, scene loading time, and the delay between user movement and image refresh. In addition, rendering stability, the proportion of frames with a constant frequency of at least 72 FPS, and the standard deviation of the frame rate were evaluated.

A combination of objective and subjective approaches was used to assess visual quality after adaptation. Objective analysis included preserving the overall shape of objects, silhouette characteristics, structural similarity of textures, perception of small details at different distances, integrity of the scene, and smooth transitions between levels of detail. For this purpose, the Chamfer Distance metric for geometric similarity and the Structural Similarity Index Measure (SSIM) metric for evaluating structural similarity of textures in Unity Editor were used. The subjective assessment was conducted in the format of a blind test with the participation of 10 people, including 5 developers of 3D and VR content and 5 users with at least 6 months of experience using VR applications. All participants previously had basic experience working with the Meta Quest 2 helmet, which reduced the impact of adaptation to the device on the evaluation results. Scene comparisons were performed individually under the same viewing conditions, and the order in which the original and optimised scenes were shown was randomised for each participant. Participants did not receive information about which version of the scene was shown at a particular moment, and after each viewing, they rated the level of visual immersion, preservation of the shape of objects, and overall perception of the environment on a five-point scale. This design of the study helped to simultaneously trace the impact of adapting 3D models on the technical performance of the VR system and on maintaining the realism of the scene.

RESULTS

In a VR environment, visualisation efficiency was associated with the need to simultaneously provide high frame rates, stereoscopic playback, and low power consumption, especially for mobile and standalone devices. In the current review of effective visualisation for VR, rendering with resource concentration in the focus area, stereoscopic rendering, cloud rendering, and energy-saving rendering were highlighted as key areas for reducing computing load, and the role of increasing resolution and intermediate frame generation technologies to improve the efficiency of mobile VR systems (Hu *et al.*, 2025). For large three-dimensional polygonal models, adaptation to VR was mainly associated with a combination of levels of detail and an approach focused on the central viewing area. The study by H. Zhang & C. Peng (2026), dedicated to real-time visualisation of large three-dimensional models with a concentration of computational resources in the focus area, showed that when selecting the level of detail, priority can be given to high geometric accuracy in the central part of the field of view, while in other areas the complexity of the model decreased. This approach was proposed specifically for VR scenes with very large polygonal models, where conventional desktop visualisation techniques created significant computational difficulties after being ported to VR.

Maintaining visual realism in VR depends not only on the model's geometry, but also on the scene's lighting. The study by G. Papaioannou *et al.* (2025) on approximate dynamic global lighting for VR noted that lighting is an important component of visual immersion, whereas for typical autonomous VR systems or mobile platforms, dynamic lighting calculations remain computationally complex. The proposed approach was aimed specifically at mid- to entry-level graphics equipment, which confirmed the need to adapt the visual components of the scene to the limited resources of VR devices. At the level of stage organisation, the effectiveness of VR adaptation was associated with a set of technical solutions, and not with one separate technique. In the applied study by Y. Wang *et al.* (2025), the optimisation techniques included the reuse of a single graphical representation of objects, batching of rendering calls, simplification of the polygon mesh for levels of detail, and culling of objects based on the viewing direction; it was noted that it was precisely these measures that ensured a stable frame rate even in the presence of thousands of objects of the same type. This gave grounds to consider the effectiveness of 3D modelling in VR as a result of matching the geometry, structure of detail levels, and organisation of the scene visualisation process.

The difference between conventional 3D models and VR-adapted models was mainly evident in the performance requirements of the interactive environment. If conventional models focus primarily on high image quality, then VR models should provide a stable frame rate, low display latency, moderate load on the Graphics Processing Unit (GPU), and a rational texture and material structure of the scene. That is why even a visually high-quality model without optimisation is often not effective enough for use in VR. The key differences between conventional 3D models and VR-adapted models are shown in Table 1.

Table 1. Comparison of conventional and VR-adapted 3D models

Comparison criteria	Conventional 3D models	VR-adapted 3D models	Analytical assessment
Main purpose of creation	High quality of an individual frame, static or pre-calculated visualisation	Stable real-time scene playback	In VR, priority is shifted from maximum detail to interactivity and performance
Number of polygons	Often high, without strict restrictions	Reduced by simplifying the polygonal grid and optimising LOD	Reducing polygonality is one of the main ways to improve the model's suitability for VR
Textures	Large and numerous texture files can be used	Textures are optimised, combined, and some details are transferred to normal maps	Texture optimisation reduces memory and rendering load without critical loss of visual quality
Materials and shaders	Often complex, focused on maximum visual effect	Simplified, subject to real-time restrictions	In VR, it is not the maximum complexity of the material that is important, but its computational feasibility
Memory and GPU loads	Increased, especially in difficult scenes	Reduced by optimising digital objects	For standalone VR devices, this directly affects the performance of the scene
Frame rate (FPS)	May decrease when porting to VR	After optimisation, it increases; the gain may be moderate, but its value depends on the complexity of the scene, the type of device, and the depth of optimisation	VR adaptation is directly related to FPS stabilisation and enhancement
Use the GPU	Often higher due to the excessive complexity of digital objects	After optimisation, it decreases; the study recorded a decrease by 6.73% and 11.72%	This is especially important for autonomous VR systems with limited resources.
Visual quality	Saved as much as possible in an isolated view	Partially simplified, but retains an acceptable similarity	In a number of models, after optimisation, the reduction of polygons by more than 99% did not lead to a critical loss of perceived quality
Suitability for an interactive VR environment	Limited without additional adaptation	High with comprehensive optimisation	VR model is evaluated as part of the entire rendering system, not as an isolated object

Source: created by the author based on S. Sukaridhoto *et al.* (2023), A. Geris *et al.* (2024), R. Grande *et al.* (2024), X. Hu *et al.* (2025)

Analysis of the table showed that the key difference between conventional 3D models and VR-adapted models was the change in design priorities. In conventional computer graphics, the focus on maximum detail of shape, textures and materials prevails, while in VR, the ability of the model to function stably in an interactive environment without overloading the system has become crucial. These characteristics showed that VR adaptation included simultaneous reduction of polygonality, optimisation of textures, simplification of materials, and reduction of memory and GPU load. It was this comprehensive restructuring of the model that provided an increase in frame rate and rendering stability, which became critical for a comfortable perception of the virtual environment. However, the adaptation did not lead to a sharp deterioration in visual quality, since with the correct combination of geometric simplification with texture maps and normal maps, the model remained sufficiently realistic. It was particularly significant that the optimised models showed not only less resource load, but also better compliance with the technical limitations of autonomous VR devices. This confirmed that the suitability of the 3D model for VR was determined not by the absolute level of detail, but by the balance between visual realism and computational efficiency. Thus, the data confirmed that VR-adapted models were functionally more efficient than conventional ones, as they better met real-time requirements, provided higher scene stability, and allowed maintaining acceptable visualisation quality at lower hardware costs.

The main areas of optimisation of 3D models for VR covered several interrelated levels of adaptation, since the effectiveness of the virtual environment was determined not only by the geometric complexity of the object, but also by the texture load, lighting parameters, levels of detail, and the overall organisation of the scene. That is why the effective adaptation of models to VR was based on a complex combination of geometric, textural, visual, LOD, and scene optimisation, each of which performed a separate function in reducing computational costs and maintaining acceptable visual quality. It is advisable to present these relationships in the form of a diagram Figure 1.

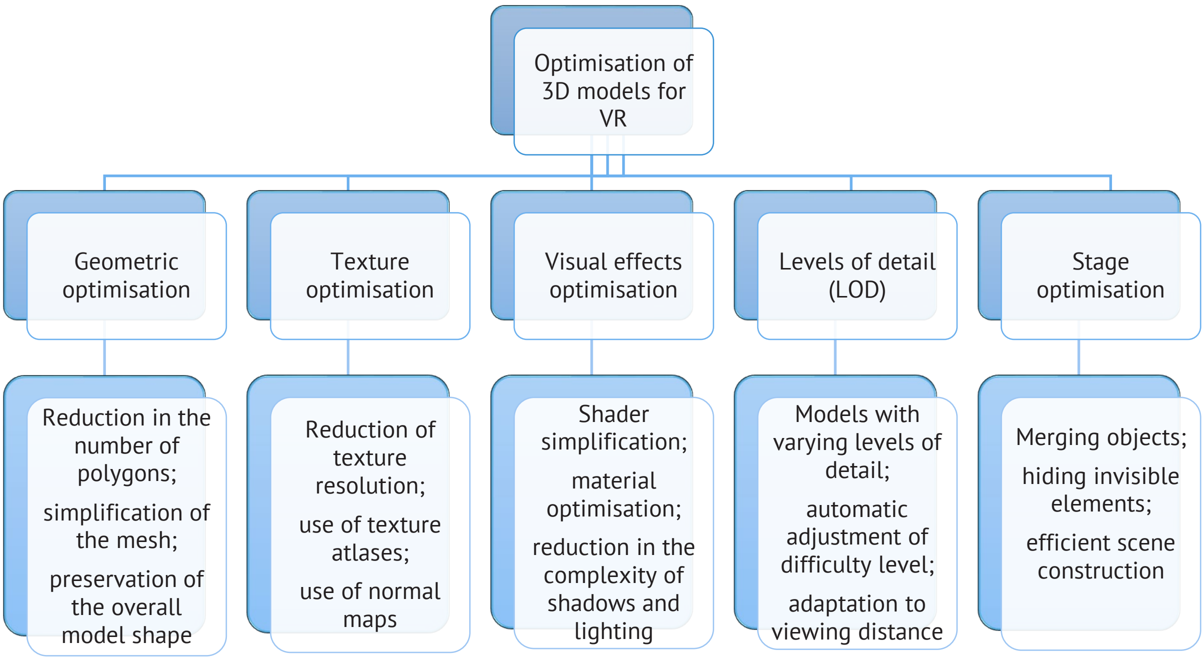

Figure 1. Main areas for optimising 3D models for VR
Source: created by the author based on R. Grande *et al.* (2024), Y. Wang *et al.* (2025), X. Hu *et al.* (2025), G. Papaioannou (2025), H. Zhang & C. Peng (2026)

Analysis of Figure 1. showed that the optimisation of 3D models for VR was complex and covered several interrelated areas, each of which performed a separate function in reducing the computational load. Geometric optimisation reduced the polygonality of the model, texture optimisation reduced the amount of graphic resources, and visual effects optimisation simplified shaders, materials, shadows, and lighting. The use of detail levels helped to dynamically change the complexity of the object depending on the conditions of perception, while scene optimisation covered the rational organisation of the entire virtual space. The data also confirmed that none of the above areas would have provided a sufficient result separately. The greatest effect was achieved precisely by combining several approaches consistent with the model type, scene parameters, and technical capabilities of the VR platform. Thus, the effectiveness of adapting 3D models to VR was determined not by a separate simplification method, but by a balanced application of a set of optimisation solutions.

The results of adapting basic 3D models to the VR environment were analysed sequentially in four key aspects: geometry, texture data, rendering, and overall scene stability. The most pronounced practical effect was observed in complex scenes where a significant number of highly detailed objects were used simultaneously. In the absence of optimisation, such a scene created a critical load on the GPU and video memory, which was accompanied by significant performance drops and reduced playback smoothness. After adaptation, even with a partial reduction in detail, the scene became suitable for full-fledged interactive interaction, while maintaining a sufficient level of visual realism. The most noticeable changes were recorded at the level of geometric optimisation. The use of simplification of the polygonal grid in combination with the development of 3-4 levels of detail (LOD) helped to significantly reduce the number of polygons without noticeably disrupting the overall shape of objects. This is especially important for VR environments where excessive polygonality directly affects rendering speed and frame rate stability. For a visual representation, the basic 3D models before and after optimisation are shown in Figure 2 and Figure 3.

Figure 2. Output high-poly 3D models prepared in Blender 3.6
Notes: model of a chair, a tree, a building facade, and an anthropomorphic character is presented.
Source: created by the author in Blender 3.6

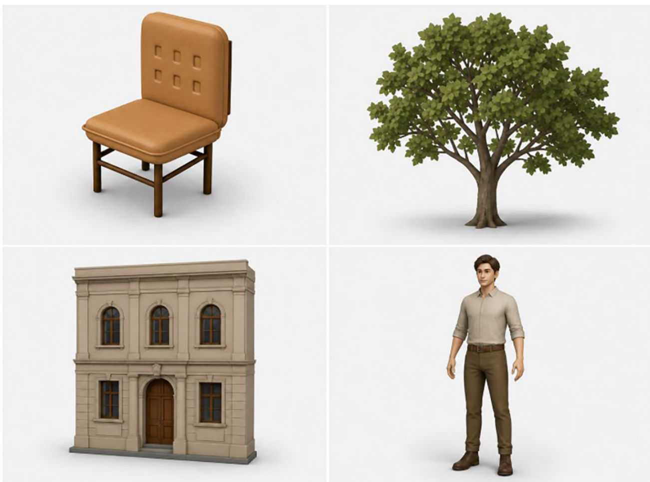

Figure 3. View of basic 3D models after a comprehensive adaptation in Unity 2022.3 for the VR environment
Notes: overall silhouette and spatial proportions of models are preserved while simplifying geometry, textures, and materials
Source: created by the author

As can be seen from Figure 2, after adaptation, the models retained their basic shape, silhouette, and functional recognition, but became less detailed at the level of fine geometry, texture saturation, and material relief. The most noticeable simplification could be traced in the crown of the tree, decorative elements of the facade, and small details of the character, while the chair retained almost the same overall design. This type of change corresponded to the task of VR adaptation: not to replace the original objects with new models, but to reduce their resource intensity while maintaining the visual realism of the scene. Quantitative changes in the main parameters of models before and after adaptation are shown in Table 2.

Table 1. Changes to the main parameters of basic 3D models before and after adapting to the VR environment

Model	Number of polygons (before)	Number of polygons (after)	Change, %	Texture size, MB (before)	Texture size, MB (after)	Change, %	Average object rendering time, ms (before)	Average object rendering time, ms (after)
Chair	248,750	12,438	-95	85	12	-86	1.2	0.4
Tree	1,456,320	58,253	-96	210	28	-87	3.5	1.1.
Building facade	3,245,800	162,290	-95	420	52	-88	8.2	2.9
Character	856,400	42,820	-95	150	22	-85	2.8	0.9

Source: created by the author based on testing in Unity3D

The data in Table 2 showed that in all the models studied, the number of polygons decreased by 95-96%, while the volume of texture data decreased by 85-88%. The greatest absolute reduction in polygonality was recorded for the building facade model, which was explained by the high initial geometric complexity of this object. Simultaneously, even after this simplification, the visual structure of the models remained sufficiently complete for perception in the VR scene. Texture data was optimised by combining textures, applying adaptive texture compression suitable for mobile VR platforms, and replacing some highly detailed colour textures with normal maps and roughness maps. This allowed reducing the total volume of textures by an average of 86.5%, which significantly lowered the load on video memory and contributed to more stable scene reproduction. At the visualisation level, a positive effect was achieved by simplifying materials and programmes for calculating visual effects. The transition from complex physically correct shading models to simplified lighting models with a minimum number of samples provided an additional reduction in the computational load. As a result, the average visualisation time of an individual object decreased in all cases: for a chair – from 1.2 to 0.4 ms, for a tree – from 3.5 to 1.1 ms, for a building facade – from 8.2 to 2.9 ms, for a character – from 2.8 to 0.9 ms. In relative terms, this corresponded to a reduction of approximately 64-67%, which directly affected the overall performance of the scene. The most significant changes were recorded at the level of overall stability of the VR environment. In the test scene, which contained 120 adapted objects, the average frame rate increased from an unstable 38-45 FPS, with drops to 25 FPS, to a stable 78-92 FPS. This showed that the adaptation turned resource-intensive conventional models into functionally efficient elements of the virtual environment, suitable for long-term interactive use without significant loss of realism.

To assess the impact of complex adaptation of 3D models on the functioning of the VR system, key performance indicators were compared before and after scene optimisation. During this stage, changes in frame rate, graphics and CPU load, video memory usage, scene loading time, and delays from motion to image update were analysed. This approach helped to quantify the extent to which geometric, textural, material, and stage optimisation tools were used to improve the suitability of the virtual environment for stable interactive use (Table 3).

Table 3. Comparison of key VR system performance indicators before and after comprehensive adaptation of 3D models

Indicator	Before adaptation	After adaptation	Change
Average FPS	42	85	+102%
Minimum FPS (1% low)	25	72	+188%
GPU load, %	94	47	-50%
CPU load, %	68	39	-43%
Device RAM/VRAM usage, MB	1,420	580	-59%
Scene loading time, s	8.4	2.9	-65%
Motion-to-photon latency, ms	38	19	-50%

Source: created by the author based on testing in Unity 2022.3 on the standalone Meta Quest 2 platform using Unity Profiler and Oculus Performance Metrics

Analysis of Table 3 showed that complex adaptation of 3D models had a positive effect not only on the average level of performance, but also on the stability of scene reproduction. Prior to optimisation, there were frequent frame rate drops below 30 FPS, covering up to 18% of the session duration and accompanied by marked intermittent movement and an increased risk of vestibular discomfort. After adaptation, the proportion of frames with a stable frequency of at least 72 FPS reached 96%, and the sample standard deviation of FPS values calculated from the data of a 300-second test session decreased from 12.4 to 3.8 (Equation 1).

This confirmed that for VR, it is important not only to increase the average FPS, but also to reduce performance fluctuations throughout the session. The greatest contribution to improving efficiency was provided by a combination of several optimisation tools. Generating detail levels combined with clipping objects that are insignificant for the current observer position reduced the GPU load by 32%. Combining textures and applying ASTC compression reduced video memory usage by 41%. Simplification of materials and shaders reduced the visualisation time of an individual object by an average of 67%. Batch processing of rendering calls and repeated use of a single graphical representation of the object had an additional positive effect in scenes with a large number of objects of the same type. It was found that excessive simplification of models reduces the quality of visual perception. In the test scenes, the reduction of polygonality by more than 98% in combination with the complete removal of normal maps led to a noticeable loss of small details already at a distance of 3-5 m: the expressiveness of the texture of facades, and the surface of tree bark decreased, which weakened the immersion effect. The most balanced mode was when the number of polygons was reduced by 94-96% while maintaining at least two levels of detail. Thus, the adaptation of 3D models turned out to be not an auxiliary, but a basic factor in ensuring the performance of VR systems, especially on equipment with limited resources. Comprehensive optimisation has ensured that the stable performance required for long-term comfortable use of the virtual environment is achieved, without critical loss of its visual credibility. It should be noted that FPS growth rates are variable and depend on the experimental conditions, scene structure, model complexity, amount of optimisation applied, hardware platform, and measurement method. Therefore, it is advisable to interpret the obtained values considering the specific configuration of the test environment.

Evaluation of visual realism after adapting 3D models to VR conditions showed that reducing geometric and textural complexity did not lead to a critical deterioration in scene perception. The analysis was performed on several aspects: preserving the overall shape of objects, the quality of texture reproduction, the perception of small details at different distances, the integrity of the scene, and the level of visual immersion. This approach helped to determine how much optimisation affected not only technical efficiency, but also the reliability of the virtual environment (Table 4).

Table 4. Evaluation of the visual realism of 3D models after optimisation for VR

Evaluation criteria	Result after optimisation	Analytical assessment
Preservation of the general shape of objects	98-99% by Chamfer Distance metric	Overall contours and spatial proportions of the models remained virtually unchanged
Stability of the object silhouette	Contours of the chair, wood, and facade of the building were preserved after the polygons were reduced by 95%	Geometric simplification did not violate the visual recognition of the main shapes
Texture playback quality	Average SSIM for textures – 0.94	Structural similarity of textures remained high
Transfer of surface microdetals	Partial loss of high-frequency details of diffuse textures was compensated by roughness maps and normals	Visual plausibility of the surfaces was preserved even when the texture volume was reduced
Perception of small details at close range	At a distance of up to 2 m, the differences were minimal	Optimised models remained convincing during typical object interactions
Perception of small details at medium and long distances	At a distance of 5-10 m, small elements were perceived as more smoothed	Loss of individual details did not destroy the overall impression of the scene
Smooth transitions between detail levels	Changes in the level of detail were almost not visually recorded	System of detail levels provided an imperceptible simplification of the model during the user's movement
Stage integrity	Preserved at a high level	Optimisation did not break the consistency of the visual environment
Level of visual immersion	Average rating – 4.7 out of 5	High stability of the stage increased the sense of presence in the virtual space

Source: created by the author based on testing in Unity

The data in Table 4 showed that the overall shape of objects and their silhouette characteristics were the most resistant to optimisation. The quality of texture reproduction remained high. Despite a partial decrease in the detail of colour textures, the structural similarity remained at 0.94, which indicated a slight loss of visual information. An additional role in maintaining the plausibility of surfaces was played by the use of normalcy maps and roughness maps, due to which it was possible to compensate for the simplification of texture resources without significantly impairing the overall perception of materials. It was found that the perception of small details significantly depended on the observation distance. At close range, which is typical for direct interaction with objects, the differences between the basic and optimised models were minimal. At medium and long distances, individual elements, such as the texture of bark, leaves, or small architectural details, became more smoothed out, but this did not lead to a loss of the integrity of the visual image. In addition, this was facilitated by smooth transitions between levels of detail, which did not create noticeable gaps in perception. Separately, it should be noted that a high level of visual immersion was provided not only by the geometry or textures themselves, but also by the stability of scene reproduction. With an average score of 4.7 out of 5, the optimised environment was perceived as visually compelling and comfortable for long-term use. This showed that in VR conditions, realism is determined not by the maximum complexity of each individual object, but by the consistency of geometry, textures, lighting, and smooth reproduction. To specify the results of objective and subjective assessment of visual quality, numerical indicators of geometric similarity of models using the Chamfer Distance metric, structural similarity of textures using the SSIM metric, and the results of blind subjective testing on a five-point scale were summarised. Summary data for individual models and distribution of participants' average scores are shown in Table 5.

Table 5. Objective indicators of visual quality of optimised 3D models

Model	Shape retention based on Chamfer Distance, %	SSIM textures
Chair	99	0.95
Tree	98.2	0.93
Building facade	98.7	0.94
Character	98.5	0.94
Mean value	98.6	0.94

Source: created by the author based on testing in Unity Editor and the results of a blind survey of 10 participants

The data in Table 5 showed that complex adaptation of 3D models to the VR environment did not cause a critical deterioration in visual quality either in terms of objective or subjective indicators. According to the results of an objective assessment, the shape retention of models using the Chamfer Distance metric was in the range of 98.2-99%, and the average value was 98.6%, which confirmed the high geometric similarity of the optimised models to the original ones. The structural similarity of textures by the SSIM metric varied between 0.93 and 0.95 with an average value of 0.94, which showed a slight loss of texture information after optimisation. The highest values were recorded for the chair model, while slightly lower values were recorded for the tree model, which can be explained by a more complex irregular geometry and a large number of small peripheral elements. To summarise the results of subjective evaluation of the optimised VR scene on a five-point scale, the average values for individual criteria and the distribution of participants' ratings were determined, which are shown in Table 6.

Table 6. Results of subjective evaluation of the optimised VR scene on a 5-point scale, n = 10

Criteria	4 points, n (%)	5 points, n (%)	Average score
Preservation of the shape of objects	3 (30)	7 (70)	4.7
Level of visual immersion	4 (40)	6 (60)	4.6
General perception of the environment	2 (20)	8 (80)	4.8

Source: created by the author based on the results of blind testing

The results of subjective evaluation also confirmed the preservation of high visual realism of the optimised scene. According to all criteria, high ratings prevailed, and the share of maximum ratings ranged from 60% to 80%. Overall perception of the environment was rated the highest, while preserving the shape of objects and the level of visual immersion were slightly lower. This showed that the optimisation carried out ensured not only an increase in the technical efficiency of the VR scene, but also the preservation of its integrity, object recognition, and comfort for user perception. Thus, the data obtained confirmed that a rational combination of geometric simplification, texture optimisation, and the use of detail levels helped to achieve a balance between performance and visual plausibility of the virtual environment.

The results of adaptation of 3D models showed not only an increase in the technical efficiency of the virtual environment, but also the practical feasibility of using them in various types of VR applications. Reducing polygonality, reducing the amount of texture data, simplifying materials, and stabilising rendering helped to use complex scenes with limited hardware resources without significantly losing visual realism. One of the main advantages was the reduction of hardware requirements, which expanded the possibilities of using VR in educational, project and production environments. An important result was also an increase in the smoothness of interactive interaction and a reduction in the risk of visual discomfort. In addition, optimisation made it easier to scale complex scenes, as it allowed increasing the number of objects without proportionally increasing the load on the system. Therefore, the practical value of optimised models was to increase the availability, stability, and functional suitability of VR solutions, which expanded the possibilities of their application implementation.

Generalisation of theoretical and practical results showed that direct use of conventional 3D models in the VR environment is ineffective, since models created without considering the requirements of interactive rendering form an excessive load on the graphic subsystem and reduce the stability of scene reproduction. The highest efficiency was achieved with a comprehensive adaptation that combined geometric optimisation, reduced texture data, simplified materials, applied detail levels, and stage optimisation. The most effective solution was not a separate technical solution, but a coordinated combination of several approaches in accordance with the type of object, its role in the scene, and the technical capabilities of the platform. It was found that the increase in performance was not accompanied by a critical loss of visual quality, and the balance between realism and speed remained a crucial factor in VR. This adaptation was particularly important for systems focused on mass or resource-limited equipment. Therefore, the use of 3D modelling in computer graphics for VR is most effective when models are initially designed or purposefully modified to meet the requirements of the interactive VR environment.

DISCUSSION

The results confirmed that the effectiveness of using 3D modelling in VR is determined not by the maximum geometric detail per se, but by the ability of the model to maintain visual credibility with a significantly reduced computational load. The study found that a comprehensive adaptation of models for the VR environment, which combined simplification of the polygonal grid, optimisation of textures, materials, detail levels and scenes, provided a sharp increase in performance without critical loss of perception quality. This result gives grounds to consider the optimisation of 3D content not as an auxiliary technical stage, but as a key condition for the functional suitability of digital objects for an interactive VR environment.

Performance improvements were achieved through local simplification of geometry, textures, materials, and stage structure for the limited resources of an autonomous device. J.A. Santos-Paz *et al.* (2025) solved a similar problem through remote visualisation, data transfer to the server, and a low-latency codec that is resistant to packet loss and is associated with data about the user's gaze direction. Thus, both approaches were aimed at ensuring smooth VR interaction, but in the first case, the key tool was content optimisation, and in the second – network computing architecture. After optimisation, the overall shape of objects remained at the level of 98-99%, which indicated that there was no critical loss of visual integrity. A similar pattern was found by Z. Yang *et al.* (2025), which, when optimising BIM- and 3D GIS models for digital doubles, reduced the average load time by 15% while maintaining 97% geometric accuracy. The difference was that their study focused on the accuracy of the spatial representation of the digital twin, while here the priority remained to provide real-time in VR. The data obtained confirmed that even within the conventional polygonal approach, a significant increase in technical efficiency was achieved due to a rational combination of geometric, texture, and stage optimisation. This correlated with the review by W. Chen *et al.* (2025), which considered modern techniques of 3D reconstruction and visualisation, in particular the Gaussian splatting-reproduction approach, as a direction for improving the speed and quality of reproduction of complex scenes. Simultaneously, the review paper outlined the general evolution of methods, while the presented results showed the practical effectiveness of classical model optimisation in an applied VR environment. Increasing the frame rate and reducing latency was accompanied by maintaining a high level of visual immersion, i.e., technical optimisation directly improved the user's perception of the scene. The study by S. Fowler & S. Souihi (2025) also emphasised that the quality of the VR experience was determined by the balance between latency and visual clarity, and its optimisation was achieved through reinforcement learning on mobile edge networks. Thus, both studies confirmed the multi-factorial nature of VR performance, but in one case the decisive factor was the preparation of 3D content, and in the other – the adaptive distribution of network and computing resources.

The results showed that optimisation of three-dimensional models was an important prerequisite for their effective use in applied VR systems. This was consistent with research by Z. Li *et al.* (2025), where VR was used as an interactive design environment. The difference was that there the emphasis was placed on the development of engineering solutions, while here – on the technical suitability of models for stable scene reproduction. A similar applied orientation was traced in the study by A. Hernández-Chávez *et al.* (2026), dedicated to visualising the network infrastructure of university campuses in mobile applications and VR. Their results confirmed that 3D modelling in infrastructure systems performed not only a demonstration, but also an analytical function. Simultaneously, this study was dominated by the visualisation component, rather than productivity optimisation. The importance of the technical quality of the VR environment for practical application was also confirmed in the study by K. Wang *et al.* (2025), where VR was seen as a safety management tool in construction. The researchers attributed its effectiveness to the ability to model professional situations and improve risk recognition. In both cases, VR acted as an effective engineering tool, although the functional purpose of its application was different. A close example of the technical use of VR was provided by L.S. de Assis *et al.* (2026), who applied photogrammetric three-dimensional models and VR to inspect tunnels. This confirmed that the combination of 3D modelling with VR was promising not only for design, but also for monitoring the state of infrastructure facilities. Thus, the results obtained fit well into the broader field of applied use of VR in engineering and technical systems.

The results showed that the value of a virtual environment was determined not only by technical stability, but also by the ability to maintain a holistic perception of the scene and user-friendly interaction. This was consistent with the research by F. Savini *et al*. (2025), in which 3D models based on unmanned photogrammetry and laser scanning were semantically enriched, simplified, and integrated into a web-based VR solution to increase the accessibility of cultural heritage. Thus, in both cases, optimisation of 3D content was considered as a condition not only for technical suitability, but also for greater accessibility of cultural experience. The educational potential of the immersive environment was confirmed in the study by S.-J. Chen *et al*. (2024), where an immersive VR approach to 3D modelling increased creativity and problem-solving abilities in younger students and reduced cognitive load compared to the usual virtual format. A similar effect was found by I. Irwanto *et al*. (2025), who recorded a statistically significant improvement in the creative attitudes and academic performance of 11th grade pupils. This showed that a well-organised immersive environment increased not only engagement, but also cognitive performance.

The importance of user interaction was clearly traced in the study by W. Zhao *et al*. (2023), where VR-based 3D modelling technology and a human-machine interaction algorithm for digital control and presentation of exhibits were proposed for the museum space. A logical approach was presented by E. Kontogiorgakis *et al*. (2024), who combined 3D reconstruction, virtual characters, and 360° video in a gamified VR narrative for cultural tourism. Thus, in cultural and museum applications, not only visibility became important, but also the ability of VR to form engagement and emotionally rich interaction. A broader theoretical context of this area was presented by A. Marougkas *et al*. (2023), who in a review of educational VR studies showed that the effectiveness of such environments was most often explained by active learning, experience-based learning, and increased engagement. In this sense, the results presented fit well with the general trend that VR was considered not just as a means of visualisation, but as a medium of perception, interaction, and cognition. Therefore, this block of research confirmed that in culture, education, and user experience, immersion was an independent factor in the effectiveness of the digital space. Thus, contemporary research has confirmed that the effectiveness of VR environments was determined not only by the technical quality of 3D models, but also by their ability to provide cognitive engagement, user-friendly interaction, and a holistic cultural user experience.

CONCLUSIONS

As a result of the study, it was found that direct use of conventional 3D models in a VR environment is ineffective, since models created without considering the requirements of interactive rendering create an excessive load on graphics and central processors and video memory. It was confirmed that the highest efficiency is achieved with a comprehensive adaptation that combines geometric optimisation, reducing the volume of texture data, simplifying materials, applying detail levels and stage optimisation. Practical testing showed that after adaptation, the number of polygons in the studied models decreased by 95-96%, and the volume of texture data – by 85-88%. The average visualisation time of an individual object was reduced by about 64-67%, which provided a significant increase in scene performance. In the VR test environment, the average frame rate increased from 42 to 85 frames per second, the minimum frame rate at 1% of the lowest values increased from 25 to 72 FPS, the GPU load decreased by 50%, video memory usage – by 59%, and the delay between user movement and image refresh – from 38 to 19 ms. This confirmed that the adaptation of 3D models is one of the key factors for ensuring the stable functioning of VR systems, especially on autonomous and resource-limited devices.

The visual quality assessment showed that the performance improvement was not accompanied by a critical loss of realism. The overall shape of the objects remained at 98-99%, the structural similarity of textures was 0.94, and the level of visual immersion was estimated at an average of 4.7 out of 5. This suggests that for VR, it is not the maximum detail of each object that is crucial, but the balance between geometric complexity, texture saturation, lighting, and playback stability. The results showed that even with a significant reduction in polygonality and the volume of texture data, the virtual environment retained the integrity of visual perception and remained convincing to the user. This showed that rational optimisation did not reduce the quality of the VR scene to an unacceptable level, but, on the contrary, provided a combination of technical efficiency with a fairly high visual plausibility. A limitation of the study was the use of a single hardware platform, a limited set of basic models, and a single test scene configuration. Further research should be directed to testing the results on other VR devices, expanding the types of virtual scenes, and applying adaptive real-time optimisation algorithms.

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CONFLICT OF INTEREST

None.

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Оптимізація 3D-моделей для візуалізації в системах віртуальної реальності

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Анотація. Актуальність дослідження зумовлена зростанням використання віртуальної реальності в освіті, медицині, проєктуванні та інженерних системах, де традиційні 3D-моделі часто виявляються надто ресурсоємними для стабільного інтерактивного відтворення. Метою дослідження було виявлення й перевірка ефективності комплексної адаптації цифрових об'єктів до інтерактивного просторового відтворення за умов обмежених апаратних ресурсів. Методологія дослідження поєднувала теоретичний аналіз із експериментальним тестуванням у Unity 2022.3 на платформі Meta Quest 2 з оцінюванням продуктивності та візуальної якості. Результати дослідження показали, що пряме використання традиційних тривимірних моделей у віртуальній реальності є малоефективним через надмірне навантаження на апаратні ресурси та нестабільність відтворення сцени. Встановлено, що найвищу ефективність забезпечує комплексна адаптація, яка поєднує спрощення полігональної сітки, скорочення обсягу текстурних даних, спрощення матеріалів, застосування рівнів деталізації та сценову оптимізацію. Після адаптації кількість полігонів у досліджених моделях зменшилася на 95-96 %, а обсяг текстурних даних – на 85-88 %. У тестовому віртуальному середовищі середня частота кадрів зросла з 42 до 85 кадрів за секунду, що підтвердило істотне підвищення продуктивності сцени. Водночас підвищення швидкодії не супроводжувалося критичною втратою візуальної якості, оскільки загальна форма об'єктів збереглася на рівні 98-99 %, а рівень візуального занурення залишився високим. Результати дослідження можуть бути використані розробниками додатків віртуальної реальності, фахівцями з комп'ютерної графіки, викладачами, проєктувальниками та інженерами для створення навчальних симуляторів, архітектурної візуалізації, медичних тренажерів і технічних систем віртуальної реальності із підвищеною продуктивністю та збереженням візуальної переконливості

Ключові слова: застосування рівнів деталізації; спрощення полігональної сітки; інтерактивність; візуалізація; рівень візуального занурення; частота кадрів