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DEVELOPMENT OF IMMERSIVE LIFE-LIKE VIRTUAL ENVIRONMENTS FOR NEXT-GENERATION EDUCATION

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The object of the study was a modular large-scale urban VR system designed for real-time standalone execution. The study addressed the absence of an engineering asset based on modular design and rule-based geometric reduction for developing large-scale urban virtual reality (VR) environments that preserve navigation-relevant realism under standalone real-time performance constraints. Existing study primarily focused on small-scale scenes or treated realism as a global aesthetic property without systematic resource allocation strategies for city-scale environments.

To solve this problem, a rule-based geometric reduction asset grounded in selective realism was developed and experimentally validated. Architectural objects were classified by spatial and functional significance (Classes A-C), and interior accessibility levels were introduced to regulate geometric complexity. A modular urban prototype comprising more than thirty architectural assets was implemented on a unified metric grid.

Geometric reduction decreased vertex count from 49,114 to 4,033 and polygon count from 89,840 to 5,615, representing more than a fifteenfold complexity reduction while preserving object hierarchy. Experimental validation (n = 20) demonstrated high perceived spatial clarity (5.9/7), low navigation error rate (1.3 errors), mean completion time of 4.8 ± 1.2 minutes, and 18% average route deviation. The framework proved applicable to standalone VR education scenarios under strict rendering constraints

Keywords: selective realism; rule-based geometric reduction; navigation metrics; immersive STEM education

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1. Introduction

Immersive technologies, such as virtual reality (VR), augmented reality (AR), and mixed reality (MR), acquired an impressive power for transfiguring the educational process, allowing for high presence and sensory engagement. These technologies have transformed traditional ways of interaction with different types of educational content, applying ideas related to telepresence, spatial cognition, and multimodal information integration. Studies indicate that a virtual reality environment results in higher engagement of students, improves the development of procedural skills, and helps knowledge transfer in areas such as engineering, medicine, and urban studies, or industrial safety [1–3].

The global transformation of education in the digital world is matched by the formulation of strategies to ensure the quality, access, and sustainability of education processes to suit the priorities of nations and international initiatives. These strategies were based on scientific studies conducted, government initiatives in the field of digital education, and recommendations from international bodies such as the United Nations Educational, Scientific and Cultural Organization (UNESCO), the Organization for Economic Co-operation and Development (OECD), the European Commission, and so on Growing interest in immersive technologies is reflected in international documents: for example, the European Union's Digital Education Action Plan (2021-2027) emphasizes the need to integrate advanced digital solutions, including VR and artificial intelligence, to improve the quality of education, ensure inclusiveness, and foster innovative educational ecosystems. Similar priorities were highlighted in analytical reports from UNESCO and the OECD, which view immersive technologies as a key tool for developing competencies in demand in the digital economy [1–4].

Any digital educational environment consists of several interconnected components: the virtual environment itself, the interaction interface, and the user performing actions within it. In most applications, the interface is created arbitrarily to reduce mental workload and minimize computational costs. However, designing virtual educational environments remains a methodologically challenging task, especially when high visual and spatial realism is required. For professional simulators, architectural visualization, and urban modeling, realism is a functionally necessary, not optional, requirement.

In the psychology of virtual environments, a distinction is made between the concepts of "immersion" – the technical characteristics of a system and "presence" – the subjective sensation of being in a digital space. High realism minimizes the distance between the virtual experience and the real world, which is critical for architectural visualization, psychological rehabilitation, and educational simulations. Furthermore, accurate 3D models ensure ecological validity for research and training, allowing users to develop mental maps and skills that accurately transfer to the physical environment.

A significant methodological gap has emerged in the development of VR educational spaces: there is still no systematic asset for creating large-scale urban environments that remain easy to navigate while preserving high realism in interaction zones and maintaining stable real-time performance. Addressing this challenge requires integrating computer graphics rule-based geometric reduction, cognitive factors of spatial perception, and urban spatial structure analysis. Therefore, research on selective-realism-based methodologies for scalable and cognitively clear urban VR environments is relevant. This relevance is certainly apparent in architectural orientation training, infrastructure navigation exercises, and experimental studies of cognitive mapping. In situations like these, realism is not merely an aesthetic feature but is more of a functional prerequisite for the acquisition of skills and ecological validity.

2. Literature review and problem statement

One of the foundational constructs in virtual reality research is presence. Presence is defined as a psychological state in which users experience a virtual environment as a real space, not as a mediated display [5]. Paper [6] introduced a widely used distinction between immersion and presence. Immersion refers to technical system properties. Presence refers to the user's subjective psychological response. This distinction remains central for interpreting empirical findings. Early theoretical works showed that presence increases when sensory cues are coherent. They also showed that cues should match user expectations. However, these works did not explain how to maintain such coherence in large-scale environments with limited computational resources.

Later studies introduced psychological fidelity [7]. This concept was further developed in simulation-based training research [8]. These studies showed that behavioral validity depends on more than sensory richness. It also depends on scenario consistency and interaction realism. Yet most experiments were conducted in small and controlled scenes. This leaves the scalability to urban-scale environments unresolved.

Recent empirical work examined how visual fidelity relates to cognitive load and learning outcomes. Stylized environments may increase motivation in entertainment contexts [9]. In training contexts, reduced realism may harm skill transfer and create cognitive incongruence. EEG-based studies suggest that higher visual fidelity may reduce mental workload. They also suggest it may support sustained attention [10, 11]. Educational VR research also reports a trade-off. Too much detail can increase extraneous cognitive load. This is described in the cognitive affective model of immersive learning [12]. Therefore, visual realism should be regulated rather than maximized.

Studies of STEM and laboratory-based VR learning environments support the value of accurate spatial and visual representation [13]. These studies report improvements in comprehension and procedural understanding. However, realism is not treated as a controllable variable in a systematic way. Resource allocation strategies are also not discussed explicitly.

Other studies link visual realism to memory encoding and exploration behavior. Higher environmental detail correlates with more structured gaze behavior. It also correlates with improved recall [14, 15]. High-fidelity simulations in medicine and industrial training are reported to strengthen embodiment. They also support stable sensorimotor coupling [16, 17]. Research on digital twins highlighted the role of materials, lighting, and scale calibration for spatial legibility [11, 15]. Despite these advances, most studies still evaluated realism locally. They did not examine realism in computationally constrained large-scale systems.

Recent reviews described a shift from demonstration-oriented VR to cognitively valid VR systems [9, 17]. However, a methodological gap remained. Highly realistic environments were usually small in scale. Large virtual cities were often simplified to meet performance constraints. The literature still lacked validated systems for allocating computational resources. It lacked assets that used the functional importance of objects and interaction zones in scalable urban VR.

The cognitive affective model of immersive learning provides a consolidated view of how immersion-related factors influence learning and cognitive load in immersive environments, and it emphasizes the need to manage visual complexity rather than maximize it [18]. Empirical studies also show that immersion and interactivity shape VR learning conditions and perceived cognitive effort, reinforcing that fidelity and interaction design must be balanced under real-time constraints [12]. In parallel, wayfinding research increasingly uses VR as an experimental medium. Comparative work reports that wayfinding behavior and spatial knowledge acquisition in immersive

VR can be comparable to real-world conditions, supporting VR-based evaluation of spatial legibility [19]. Dedicated VR research tools are also developed to measure wayfinding behavior in complex multi-story layouts with recorded trajectories and navigation decisions [20].

From the production and rendering side, procedural and modular methods are used to generate city-like environments through reuse rather than repeated modeling of every component [21]. Real-time large-scale rendering studies propose resource-aware loading and prioritization strategies to improve stability in massive scenes [22]. Recent research on urban 3D models also emphasizes systematic Level-of-Detail representations for buildings as a practical requirement for maintaining stable performance while preserving structural cues necessary for scene interpretation [23].

Along with it, recent research showed that visual realism functioned not as a single global determinant of user outcomes, but as a controllable design variable and that its effects depended on the targeted metric and task context. The higher visual fidelity was the higher presence tracked, though it had not consistently improved cognitive outcomes in parallel. Controlled comparisons between high- and low-fidelity environments reported a significant presence increase under higher fidelity, while no corresponding effect had been observed for context-dependent forgetting and source-monitoring errors, which suggested that realism benefits had remained outcome-specific and task-dependent [24]. Similarly, evidence from educational implementations indicated that immersion level had influenced presence, but the magnitude of this effect had been moderated by user-level factors such as prior VR experience, which supported treating fidelity as a tunable parameter rather than a universal quality target [25].

Except perceptual effects, VR systems remained constrained by a persistent engineering requirement: high-resolution, low-latency rendering under mobile or standalone compute budgets. Recent synthesis work emphasized that stable performance under these constraints had increasingly relied on a combination of efficiency strategies, including foveated rendering, stereo acceleration, cloud-assisted pipelines, and low-power rendering methods [26]. Foveated rendering positioned as a resource-aware mechanism because it had explicitly redistributed computation according to human visual sensitivity. A recent state-of-the-art survey consolidated major foveated rendering paradigms, including foundational principles, input data types, and implementation patterns, and it framed foveation as a systematic means of reducing computational load while preserving perceived foveal quality [27]. In general, these developments aligned with the view that scalable VR – especially on standalone headsets – had required explicit budgeting and prioritization mechanisms rather than uniformly high fidelity across all scene components. These limits were considered more in city-scale VR, where large spatial extents and heterogeneous asset distributions made uniformly high-fidelity modeling infeasible under real-time requirements. Urban-oriented work on virtual city information models highlighted the practical role of structured levels of detail and scenario-based representations in participatory and decision-making contexts, and it emphasized that urban VR environments needed to remain navigable and interpretable while operating within performance limits [28]. In parallel, development-facing contributions introduced tooling for systematic Level-of-Design (LoD) classification of 3D models, with the aim of reducing ambiguity in LoD assignment and enabling more consistent asset preparation for resource-constrained immersive applications [29]. As a result, these findings reinforced the need for resource-aware, rule-guided allocation of geometric and visual fidelity according to functional and spatial importance, rather than uniform realism across an entire urban scene.

Existing studies defined the basis in terms of psychological foundations of VR experience especially visual fidelity and interaction cues related to presence, cognitive load, and behavioral validity in controlled (small-scale) environments. However, these works rarely transformed the findings into 3D environments. As a result, there were only limited guides on how to maintain selective fidelity in terms of VR scene containing the geometric budgets in terms of spatial importance.

3. The aim and objectives of the study

The aim of this study was to develop a modular rule-based geometric reduction system for scalable urban VR environments that preserved navigation-relevant visual cues while ensuring stable real-time performance. The study focuses on an urban standalone VR environment and on engineering rules for selective realism-based geometric budgeting.

To achieve this aim, the following objectives were defined:

– to formalize selective realism as an operational rule set for geometric budgeting in large-scale urban VR (including object classes and interior accessibility levels);

– to develop a structured prioritization system that links functional/spatial importance of scene components to differentiated geometric and visual budgets;

– to implement a scalable modular urban VR prototype based on the proposed asset library and budgeting rules and to generate multiple city configurations;

– to validate the proposed framework using quantitative geometric reduction metrics, real-time performance indicators, and user-level navigation metrics.

4. Materials and methods

The object of the study was a scalable modular urban virtual reality environment designed for real-time standalone execution. The subject of the study was a functional prioritization system for architectural assets and interior accessibility in an urban VR scene. The main hypothesis of the study stated that selective realism-based functional prioritization of scene components would significantly reduce geometric complexity while preserving navigation efficiency and perceived spatial clarity in a large-scale standalone urban VR environment.

The study assumed that urbanistic environment elements contribution could be represented as a discrete prioritization scheme, while the interaction within them was shown as accessibility levels. Along with it was supposed that significant features of buildings would be enough to preserve navigation based visual cues under geometric reduction. The final assumption was the limitations of the standalone headset execution profile including scalability and real-time performance.

The simplifications adopted in the study were as follows. The scene consisted of the limited number of the asset's models was assumed as suggested module's representation rather digital twin along with the geometric budgeting implemented as vertex and triangle assets. The lighting concept was also simplified through baking approach to provide stability concerning on navigational stability and spatial clarity. Regarding fully symmetrical baseline comparison with a non-reduced high-load version was not included and represented as it could not be realized under identical standalone conditions.

To test the hypothesis, the virtual environment was developed using the following sequential workflow stages:

1) formalization of selective realism rule;

2) development of a modular architectural asset library;

3) prototype implementation;

4) validation under standalone VR constraints.

Blender was used as the primary 3D modeling environment due to its parametric flexibility, open-source reproducibility, and precise geometric control. All architectural components were constructed on a unified metric grid to ensure scale coherence, modular interoperability, and compositional consistency across configurations. The grid enabled flexible recomposition of urban layouts without modifying base geometry. The modularity of such solution creates potential for the synthesis of common structural elements of a whole (façade units, window and balcony units, stair sections) that can be combined with any type of design configuration, without altering the underlying geometry. Standard reference points enable the creation of numerous urban morphologies, ranging from everyday block development to industrial and mixed-use residential zones, on the basis of the same or similar standard reference points without changing single components. This method achieves substantial reduction of the labor costs and scalability of the virtual environment.

For realism management and to allocate computing resources according to spatial importance, a spatial importance ranking system (Fig. 1) was introduced. The urban environment was classified into three categories:

– dominant objects (Class A) – which are unique architectural elements and landmarks that are important for user navigation and mental map making. These objects are produced with extensive geometric detail and distinct textures;

– background buildings (Class B) – which are typical residential and office buildings and visually present the space of a city. It was developed using modular components with optimized geometry;

– peripheral objects (Class C), simplified models with minimal polygonal complexity; the purpose was to build a background line and to define a horizon line. With this type of ranking, one could focus on the visual complexity of the scene, with a heightened amount of realism in active interaction points and decreased load in peripheral areas.

Building interiors are among the most resource-intensive parts of VR scenes. A series of interior accessibility levels was proposed for optimizing the computing load (Fig. 2):

– level 1 (visual): no interior; windows use opaque materials/shader with a parallax mapping to get the illusion of depth without additional geometry;

– level 2 (transit): access restricted to entry points (halls, entrances) from the outside;

– level 3 (full): the building is completely open to the users; all rooms are interactive and partake in the user experience. Accessibility levels hierarchical made it possible to view interiors as manageable levels, responsive to certain educational or research needs.

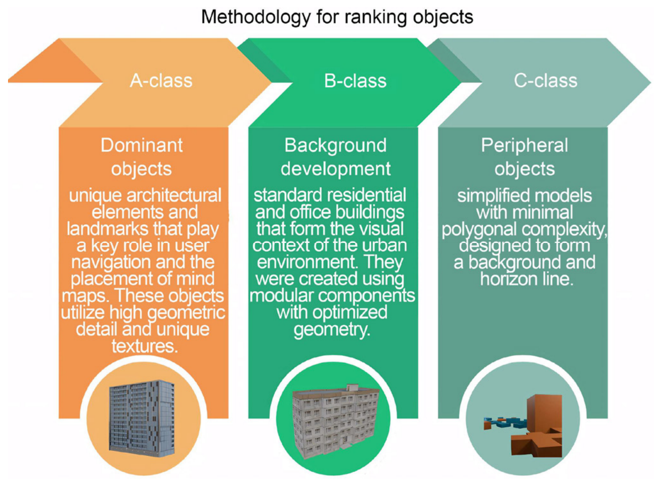


Fig. 1. Screenshot of the virtual environment using the proposed object ranking system

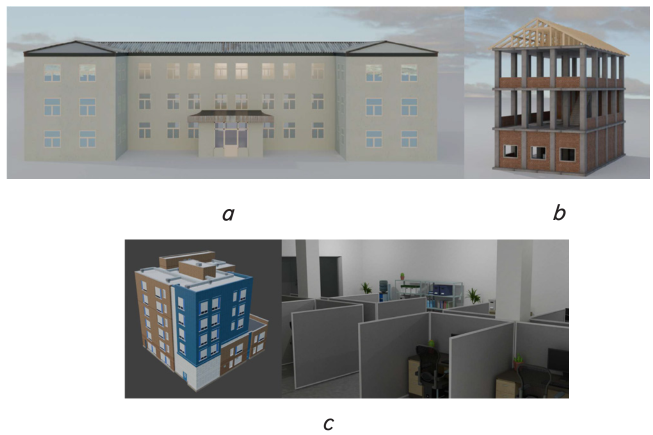


Fig. 2. Screenshots of different interior accessibility levels: *a* — example of a level 1 building; *b* — example of a level 2 building; *c* — example of a level 3 building

The virtual urban environment was created with modular 3D modeling in Blender to realize visual fidelity, cognitive consistency, and computational efficiency. Architecture units were realized as independent modular elements linked to a single metric grid, for easy scaling, spatial consistency, and flexibility of the urban form design. Geometric rule-based reduction and physically based rendering (PBR) principles were implemented for the modeling process, maintaining major architectural motifs while improving polygonal layout (Fig. 3).

Special focus was placed on the functional effect of objects on a city: buildings and infrastructure areas were ranked according to spatial importance and anticipated level of user interaction. This facilitated a focused variability on the amount of detailed detail and visual richness of the models, thereby focusing computing resources on applications involving active navigation and cognitive engagement. The modularity and adjustable level of detail in the creation areas helped to achieve good variability at the created locations for the use of built elements without a remodeling of the space, and thus, provide logically constructed and navigable virtual urban spaces. Hence, the usage of Blender was not restricted to the instrumental purpose of designing geometry, but was part of a wider engineering pipeline of selective realism with a view to achieve scalable and scientifically valid digital replicas of the urban environment for use within educational VR and experimental studies.

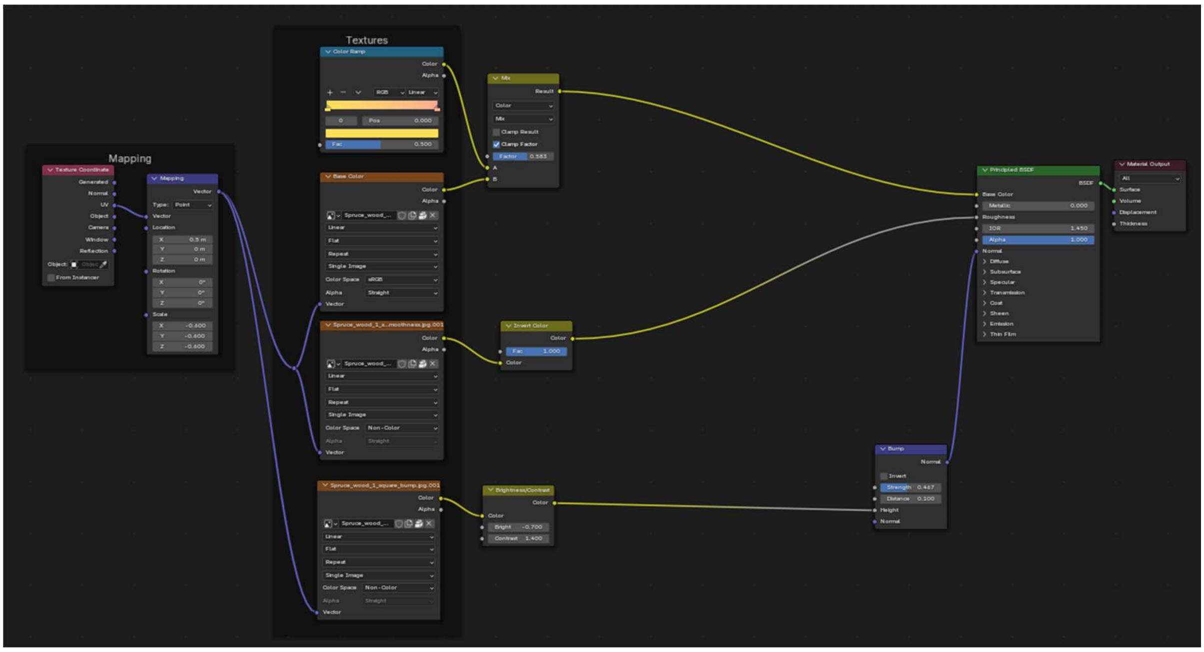


Fig. 3. Example of physically based rendering material and parameter settings

Façades and landscaping elements had been textured in consideration of the scale of the users' perception in VR to provide a consistent vis-à-vis quality at close proximity and distanced settings. A prototype of a virtual city block (residential, public and industrial buildings) was completed in the last stage.

The experimental validation was conducted using a Meta Quest 3 (512 GB) headset operating in standalone mode. The VR prototype was executed natively on the device without external PC streaming. All participants used the same hardware-software configuration under identical testing conditions to ensure measurement consistency. The environment was rendered in real time using the headset's native standalone performance capabilities.

The prototype was then utilized to validate the proposed rule-based geometric reduction framework, to test its functionality and prove its efficiency. The testing centered on rendering stability, how hierarchical realism distribution affected performance and keeping a comfortable user experience. The Results section presents quantitative performance metrics and optimization results. The geometric reduction task can be formulated as minimizing polygon count subject to preservation of:

1) object hierarchy;
2) landmark-defining features;
3) spatial topology consistency.

5. Results of the proposed engineering pipeline for the immersive life-like virtual reality spaces development

5. 1. Selective realism engineering pipeline

The study showed authors' workflow for creation of a modular urban VR environment based on the principle of selective realism. The workflow was described as a sequential four-stage process (Fig. 4) integrating functional classification, budgeted geometric reduction, and modular assembly to support real-time performance while preserving navigation-relevant visual cues.

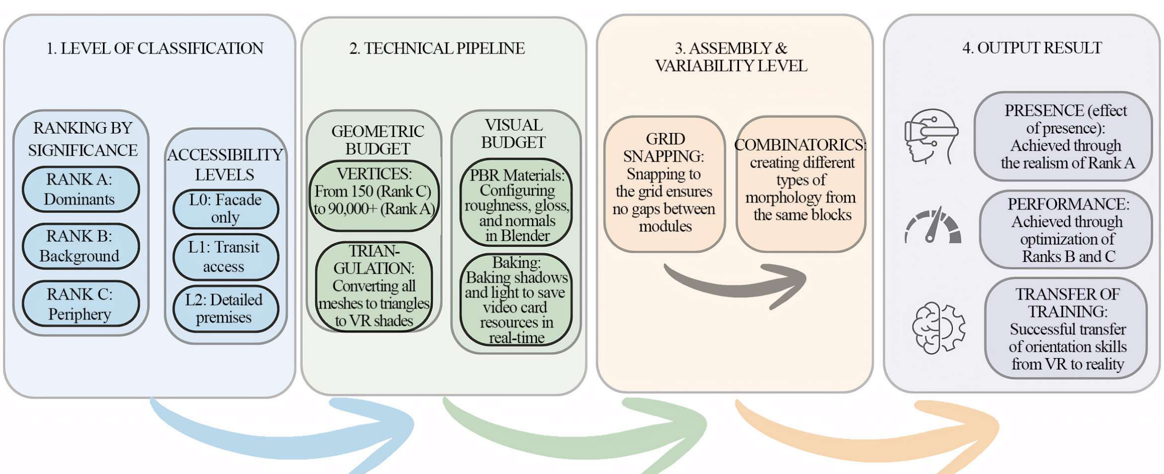


Fig. 4. Selective realism engineering workflow

At Stage 1, scene components were prioritized according to functional significance (Ranks A–C) and interior accessibility levels (L0–L2). At Stage 2, geometric and visual budgets were applied, including vertex targets, PBR material setup, and precomputed lighting and shadow baking. At Stage 3, modular elements were assembled using metric grid snapping and composition rules to ensure spatial consistency. At Stage 4, the resulting environment was integrated and tested in a VR-ready configuration to verify that the defined budgets and prioritization rules were maintained during practical use.

5. 2. From functional significance to visual budgets: a prioritization system

A structured prioritization system was developed to regulate geometric complexity according to spatial and functional significance rather than applying uniform polygon reduction. The proposed system integrated object-level ranking (Classes A-C) with interior accessibility levels to define differentiated geometric budgets at the content preparation stage.

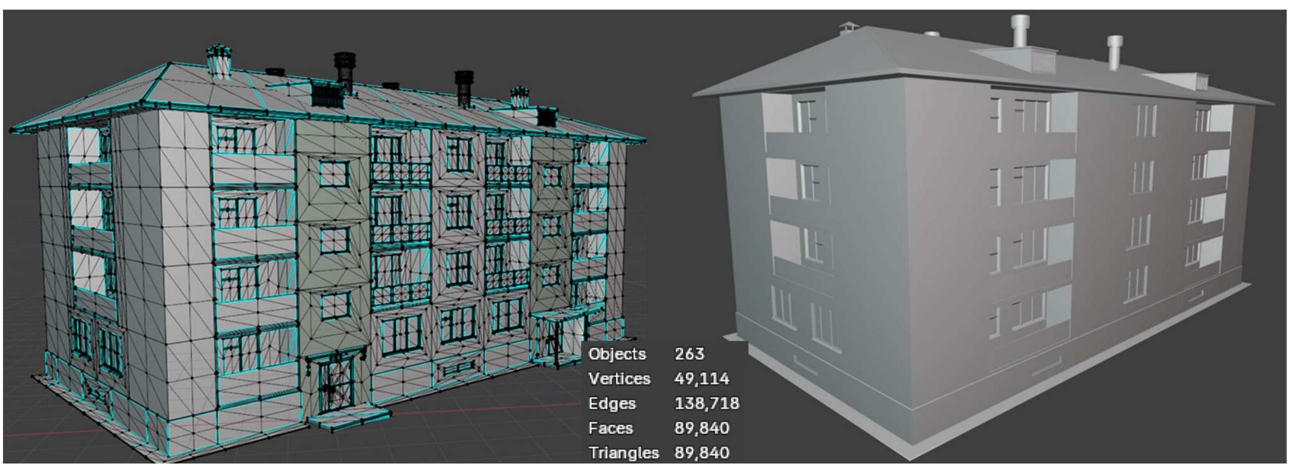
Class A objects (landmarks and navigation anchors) were preserved with characteristic façade features; Class B objects retained modular façade elements with controlled repetition; Class C objects were reduced to minimal geometric shells sufficient to maintain skyline continuity and spatial enclosure. Interior accessibility levels further constrained geometric allocation: Level 1 excluded interior geometry, Level 2 preserved entry zones only, and Level 3 retained full interior structure (Fig. 2). Together, these rules ensured that computational resources were distributed according to navigation relevance and interaction intensity.

During rule-based reduction of a representative building model, geometric complexity was reduced while preserving hierarchical organization and landmark-defining features (Fig. 5). The total number of scene objects remained constant (263 before and after reduction), maintaining structural composition and interactive topology (Table 1).

Table 1

Comparison of indicators before and after optimization

Parameter	Before optimization	After optimization
Objects	263	263
Vertices	49 114	4 033
Edges	138 718	9 412
Faces	89 840	5 615
Triangles	89 840	5 615



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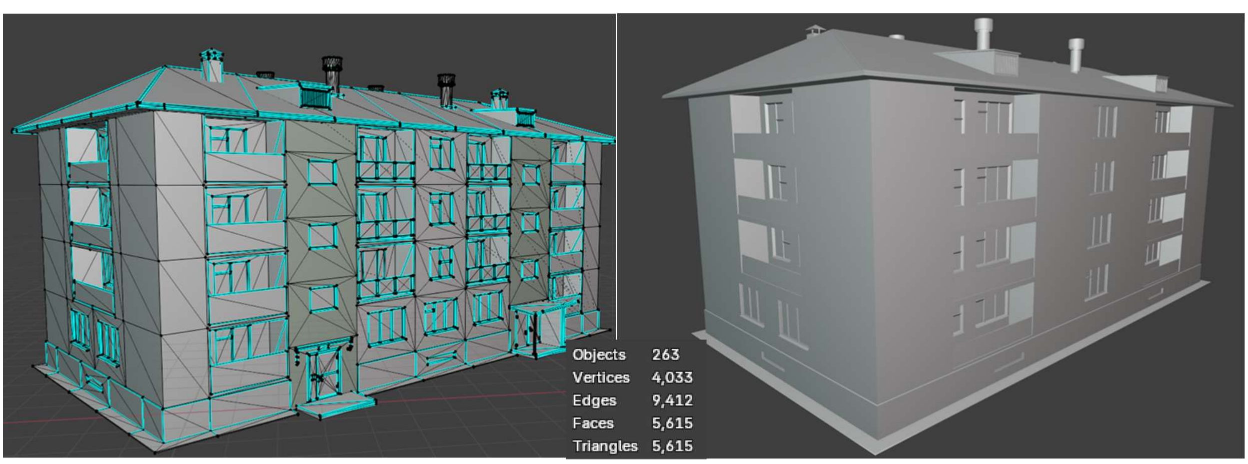

b

Fig. 5. An example of 3D model optimization:
a — screenshot of the model before optimization; *b* — screenshot of the model after optimization

Vertex count decreased from 49,114 to 4,033 and polygon (triangle) count from 89,840 to 5,615, representing more than a fifteenfold reduction in geometric load (Table 1). These results demonstrate that controlled rule-based prioritization enables measurable complexity reduction while preserving perceptually significant spatial structure under standalone real-time constraints.

5. 3. Implementation of a scalable modular urban prototype

Practical testing of the assembly stage confirmed that modular combinatorics and metric grid snapping enabled the generation of variable urban morphologies without exceeding predefined geometric budgets (Fig. 6). Based on a library of more than thirty architectural assets constructed as modular components, twelve distinct urban layout configurations were generated, including residential blocks, mixed-use clusters, and industrial-type arrangements.

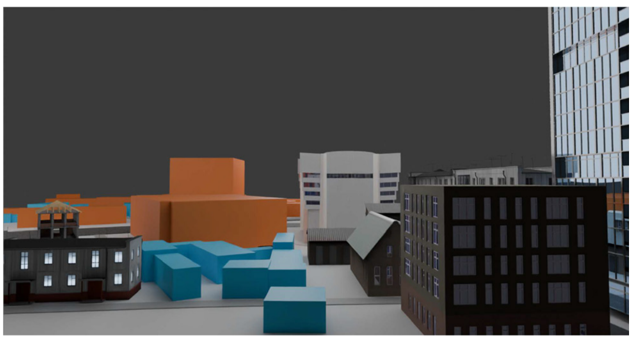

Fig. 6. Screenshot of the virtual environment using the proposed object ranking system

Across these configurations, the total object count remained stable (263 objects per scene), and geometric complexity remained within the defined reduced budget (4,033 vertices and 5,615 triangles for representative Class B buildings; Table 1). Variations in layout density were achieved through combinatorial rearrangement of façade modules, corner elements, and structural units without introducing additional geometric primitives.

The unified metric grid ensured consistent alignment and scale across all assets. It allowed modification of block dimensions and street width while keeping the overall structure coherent. Scene recomposition was performed without remodeling the base assets. The grid-based recomposition also did not increase vertex or polygon counts beyond the reduced budgets already defined.

The achieved geometric reduction (more than fifteenfold decrease in vertices and triangles compared to the initial model; Table 1) directly decreased rendering workload. It also supported stable real-time execution under standalone hardware constraints. As a result, the prototype showed that scalable urban variability could be obtained through rule-based modular assembly while keeping fixed geometric budgets and preserving the navigation-relevant structural hierarchy.

5. 4. Validation of the proposed solution

To examine navigation performance in the virtual urban environment, an experiment was conducted with 20 students. Task completion time, number of navigation errors, route length, and subjective navigation ease were measured. A navigation error was defined as:

1) entering an incorrect area and remaining there for more than 10 seconds;

2) returning to a previously traversed segment with a length greater than 5 meters.

The optimal route length was defined as the shortest path between predefined points in the environment. All participants used the same hardware–software configuration, which ensured consistent measurement conditions.

The mean task completion time was 4.8 minutes (SD = 1.2). Navigation errors averaged 1.3 per participant. Route length exceeded the optimal distance by 18% on average, which reflected typical initial adaptation in an unfamiliar spatial layout. Subjective navigation ease was measured on a 7-point Likert scale and had a mean value of 5.9. This result indicated that participants generally perceived the environment as easy to understand and that landmarks remained distinguishable (Table 2).

Table 2

Navigation metrics in the virtual urban space ($n = 20$)

Metrics	Indicators
Average time to complete navigation tasks, min	4.8 ± 1.2
Average number of navigation errors per participant	1.3
Average excess of route length over optimal, %	18
Subjective assessment of navigation ease (Likert scale 1–7)	5.9

Standalone execution on Meta Quest 3 imposed strict performance limits. In the reduced-complexity version, the environment remained usable for navigation tasks, and participants reported stable spatial understanding. A fully symmetrical baseline comparison was not implemented. The high-load version could not be executed reliably on Meta Quest 3 in standalone mode because rendering became unstable and the frame rate dropped below a comfortable level. This hardware limitation prevented a direct task-matched comparison between the reduced and high-load versions under identical conditions. Therefore, this paper showed a single-condition validation under standalone constraints and the baseline comparing was set as a part of future work.

6. Discussion of results on application of the selective realism system

This study examined the design and validation of a scalable urban VR environment in which visual realism was managed selectively to preserve navigation-relevant cues while maintaining real-time performance. The results demonstrated that selective realism-based resource-aware prioritization strategy enabled substantial geometric reduction while preserving navigational readability and perceived spatial clarity.

The proposed selective realism-based modular system can be applied to VR-based education and research scenarios that require navigation in complex-built environments, such as architecture and urban planning training, infrastructure orientation tasks, and spatial reasoning laboratories. Practical use requires:

1) a modular asset library aligned to a metric grid;

2) an explicit ranking of scene elements by navigation and interaction relevance (Classes A-C);

3) predefined interior accessibility levels to control geog metric budgets.

Under these conditions, the framework is expected to reduce content preparation and rendering load while preserving landmark legibility and spatial coherence, enabling scalable standalone deployments and reproducible urban VR scenes suitable for iterative educational use.

The experimental findings linked quantitative rule-based geometric reduction outcomes (Fig. 5; Table 1) with user-level navigation indicators (Table 2). Although geometric complexity was reduced more than fifteenfold, landmark-defining façade features and structural hierarchy were preserved. This preservation plausibly supported cognitive mapping processes, as reflected in the observed low navigation error rate and high subjective clarity scores. The observed navigation performance and high subjective clarity ratings suggested that selective rule-based geometric reduction did not degrade functional spatial perception under the tested conditions.

Unlike approaches that treat realism as a global stylistic property (e.g., realistic versus stylized environments), the present framework operationalized realism as a functional variable determined by object significance and interaction relevance. Previous empirical studies often investigated small or localized scenes and did not address city-scale implementation under real-time VR constraints [5–11, 17–15]. Conversely, engineering-oriented optimization methods typically targeted geometric reduction without systematically linking optimization decisions to perceptual functions relevant to navigation [11, 12, 15]. The proposed framework integrated these dimensions by combining quantifiable geometric reduction metrics with user-level validation, thereby bridging perceptual theory and performance-driven optimization.

Overall, the findings supported the hypothesis. Performance-aware selective realism reduced computational load while preserving navigation-relevant perceptual structure in scalable urban VR. Additional studies were required to include controlled baseline comparisons and expanded measurement instruments to strengthen causal conclusions and generalizability. The features of the study were the integration of perceptual VR theory with rule-based geometric budgeting at the content preparation stage, supported by quantitative reduction metrics and user-level navigation performance indicators.

Several limitations should be acknowledged. First, the experiment was conducted in a controlled laboratory environment. It used a single hardware–software configuration. This limited generalizability across different VR systems. Second, the sample size was relatively small. Participants were also non-experts. This limited direct conclusions about expert users and long-term training. Third, navigation tasks were performed without external aids such as maps or compasses. This strengthened internal validity. However, it may have reduced ecological validity in applied settings.

Importantly, the study did not include a fully symmetrical baseline condition. It did not compare the reduced environment with a high-load non-reduced version under the same navigation tasks. Such a comparison would support stronger causal conclusions about the effect of rule-based geometric reduction on navigation outcomes. In addition, the measurements focused on behavioral and subjective indicators. Future work should add attention and workload measures. Examples include eye-tracking, physiological proxies, or cybersickness indicators. This would provide a more complete explanation.

Finally, skill transfer was inferred indirectly. It was based on navigation performance and perceived clarity. It was not measured with delayed retention or real-world transfer tests. Longitudinal and comparative experiments are needed to evaluate transfer directly.

Future study should extend the approach to more urban morphologies. It should also automate estimation of object significance. It should test task-driven, multi-user, and interaction-rich scenarios. Methodological challenges include defining robust and task-sensitive criteria for functional significance across user groups. Technical challenges include keeping landmark semantics consistent at larger scales. They also include maintaining stability across different VR hardware configurations.

Although the study did not include a fully symmetrical baseline comparison, several indicators remained informative. Scene composition was preserved. Navigation and clarity results were consistent. These findings suggested that selective realism-based rule-based geometric reduction was compatible with functional spatial orientation under the tested conditions. Future work will use controlled comparative designs to statistically test differences between fidelity levels.

7. Conclusion

1. Selective realism was defined as a controlled asset for reducing scene complexity. Realism was treated as a design variable that could be managed during content preparation. Functionally important elements, such as landmarks and navigation-relevant structures, were preserved at higher fidelity. Secondary elements were simplified. A rule-based procedure was used to determine functional importance and to guide geometric reduction under limited computational resources.

2. A ranking system was developed during the content preparation stage and was quantitatively validated. The system linked geometric reduction decisions to the functional role of scene elements instead of applying uniform polygon reduction. Geometric complexity was reduced by more than fifteenfold while preserving object count and structural hierarchy. Scene composition was maintained, and the arrangement of elements was not altered.

3. A modular urban VR prototype was constructed using the proposed asset. More than thirty architectural assets were integrated into a unified metric grid. This enabled generation of diverse urban morphologies without redesigning base geometry. The reduced-complexity model supported real-time rendering under the tested configuration. Landmarks remained distinguishable, and the spatial structure of the environment remained consistent during evaluation.

4. Experimental validation was conducted with 20 parp ticipants performing navigation tasks. Task completion time was 4.8 ± 1.2 minutes. The mean error rate was 1.3 errors per participant. Route deviation reached 18%. Participants reported high spatial comprehensibility (5.9/7). These results indicated that selective realism-based geometric reduction did not impair functional navigation under reduced geometric complexity.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors acknowledge that the ChatGPT tool (OpenAI, model GPT-4o) was used during manuscript preparation. This tool was used exclusively for language editing (checking grammar, spelling and punctuation) without changing the context of the manuscript. No significant sections of the manuscript were generated or modified using AI. All AI-generated edits were reviewed and approved by the authors. The authors bear full responsibility for the final manuscript.

Authors' contributions

Yevgeniya Daineko: Conceptualization, Methodology, Writing-original draft; **Dana Tsoy:** Conceptualization, Writing-original draft, Writing-review&editing; **Kuandyk Akshulakov:** Funding acquisition, Project administration, Supervision; **Askar Mustabekov:** Project administration, Supervision, Resources; **Evgenij Makarov:** Resources, Supervision; **Umitkhan Turzhanov:** Software, Investigation, Data curation; **Miras Uali:** Visualization, Software; **Regina Sharshova:** Writing-original draft, Writing-review&editing.

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