PROCEDURAL DIGITAL TWIN GENERATION FOR CO-CREATING IN VR FOCUSING ON VEGETATION

L. Thuvander*, S. Somanath, A. Hollberg

Dept. of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden – (liane.thuvander, sanjay.somanath, alexander.hollberg)@chalmers.se

Commission IV, WG IV/9

KEY WORDS: Co-creation, Data Pipeline, Digital twin, Green Structures, GIS, Procedural Generation, Vegetation, Virtual Reality.

ABSTRACT:

An early-stage development of a Digital Twin (DT) in Virtual Reality (VR) is presented, aiming for civic engagement in a new urban development located in an area that is a forest today. The area is presently used for recreation. For the developer, it is important both to communicate how the new development will affect the forest and allow for feedback from the citizen. High quality DT models are time-consuming to generate, especially for VR. Current model generation methods require the model developer to manually design the virtual environment. Furthermore, they are not scalable when multiple scenarios are required as a project progresses. This study aimed to create an automated, procedural workflow to generate DT models and visualize large-scale data in VR with a focus on existing green structures as a basis for participatory approaches. Two versions of the VR prototype were developed in close cooperation with the urban developer and evaluated in two user tests. A procedural workflow was developed for generating DT models and integrated into the VR application. For the green structures, efforts focused on the vegetation, such as realistic representation and placement of different types of trees and bushes. Only navigation functions were enabled in the first user test with practitioners (9 participants). Interactive functions were enabled in the second user test with pupils (age 15, 9 participants). In both tests, the researchers observed the participants and carried out short reflective interviews. The user test evaluation focussed on the perception of the vegetation, general perception of the VR environment, interaction, and navigation. The results show that the workflow is effective, and the users appreciate green structure representations in VR environments in both user tests. Based on the workflow, similar scenes can be created for any location in Sweden. Future development needs to concentrate on the refinement of buildings and information content. A challenge will be balancing the level of detail for communication with residents.

1. INTRODUCTION

1.1 Background

Digital tools and digital twins (DT) are increasingly used in urban design and planning processes, and DTs are often represented on 2D-screens (Ketzler et al., 2020; Gil, 2020). Virtual Reality (VR) allows users to immerse themselves in the environment of the DT to support the understanding of proposed development plans, communicate their perceptions, and articulate their own proposals. VR is increasingly applied in urban design and planning process to involve citizens in the decision-making process, e.g., in inaccessible areas (Fares et al., 2018), redesign of public parks (van Leeuwen et al., 2018), or smart city developments (Dembski et al., 2020) including gamification (West et al., 2019).

Fares et al. (2018) tested VR to engage citizens in the urban design process and reduce the gap between decision makers and citizens. Two VR models were used, one with limited interactivity and one that is highly interactive. Enabling interactivity in the VR application resulted in increased ease-of-use and indicated that participants are more actively engaged in how they make decisions within the application. Generally, the study showed that VR tools allow citizens to participate in the planning process remotely and as a result less time is consumed. In a redesign of a public park, van Leeuwen et al. (2018) tested VR in a municipal process of civic participation. Regarding the VR technology, they concluded that VR headsets proved to be equally effective compared to other display technologies in informing citizens during decision. However, VR headsets provided higher engagement and more vivid memories than viewing the designs on non-immersive displays. West et al. (2019) adopted a user-centered design method to develop an immersive storytelling game to educate participants on the importance of various planning and energy policies. The results from engaging with 250 participants showed that over ninety percent of the participants enjoyed the game and learned something new; a third of the participants were encouraged to continue engaging with energy issues. The possibility of VR to quickly visualise and engage participants through interactivity and feedback enhanced the utilisation of VR's capabilities to have a profound effect on the participant. Despite of advances in VR applications in citizen engagement and participation, one of the challenges in the domain of VR for landscape architecture is the efficient validation of virtual landscape models (Portman et al., 2015). The extent to which it is possible to reproduce botanically realistic vegetation including the details of plants, twigs, flowers etc. remains to be explored.

While many of the articles on VR and its application in citizen participation discuss the design of the interactivity within the application and its potential benefits for engaging with citizens, they do not elaborate on the methods used to develop the 3D models used in the visualization. High quality 3D models or DT models are time-consuming to generate, especially if the aim is to use them in VR applications (Stoter et al., 2019). Current methods of model generation require the developer to manually design the virtual environments and they are not scalable when multiple scenarios are required to be generated as a project progresses (Fares et al., 2018; Fegert et al., 2019.; Van Leeuwen et al., 2018). However, developing procedural workflows for

* Corresponding author

automated generation of 3D data is sought after in urban DT research. Early attempts of procedural 3D reconstruction of the natural and built environment applied GIS (Geographic Information Systems) and visual analysis techniques to generate additional datasets from satellite data. E.g., Rajpriya et al., (2014) generate Level of Detail 1 (LOD) 3D City models implementing a procedural pipeline that uses Cartosat-1 stereo images and high resolution IKONOS satellite data for regions where high-quality GIS data was unavailable. The workflow generates a Digital Elevation Model (DEM), images, extracts building footprints and generates 3D buildings using both semi-automatic and automatic methods. In regions with additional GIS data such as building footprints and DEM's, the process of generating LOD1 models is more convenient. Prechtel (2015) developed a technique to upgrade a large scale 2D GIS dataset for buildings and terrain to a schematic 3D model. Buildings are generated by extruding the building footprints and the roofs by using a set a shape descriptors. However, these studies did not aim for photorealism in favor of more efficient data models and adopting a strategy of "Level of Abstraction transition" (Semmo et al., 2012), using stylised visualization. Visualizations of the landscape and vegetation is representative and uses a random distribution of adjustable density.

Efforts concerning modelling of elements representing natural environment are often limited to water and terrain, only a few focus on forest or vegetation. For example, Alomia et al. (2019) discuss the development of an automatic and procedural pipeline for the generation of 3D buildings and visualization in a visualization software. The authors apply a similar approach of generating LOD1 buildings as described above, overlaid on a 3D terrain. In addition, the 3D models are textured using orthographic satellite images for the ground and textures for the building facades and roofs. Other scholars, e.g., Zhang et al. (2017) developed optimization approaches for rendering vegetation and tested for efficacy using the 3D computer graphics game engine Unreal Engine (UE). However, Alomia et al. (2019) and Zhang et al. (2017) do not address realistic visualization and representation of vegetation in their workflow. There are a few studies that concentrate on realism for vegetation representation. Shan & Sun (2021) designed a VR landscape planning simulation system including a display layer and 3D image processing technology. Huang et al. (2019) addressed the challenges of modelling natural environments where users value realism. They developed a prototype for VR visualization applications for forests that balance graphical realism and scientific accuracy, translating ecological model output data into a high-fidelity VR experience that allows users to walk through forests of the future. A 3D user interface (3DUI) was implemented using the UE Blueprint, the forest procedurally modelled in Esri CityEngine and other ecosystem components were added in UE. However, Shan & Sun (2021) and Huang et al. (2019) modelled only limited landscape areas. Bao et al. (2012) present a framework for rendering large-scale forest scenes realistically and quickly with emphasis on leads and shadows. They constructed a series of LOD models for trees to compress the overall complexity of the forest in view-dependent forest navigation able to render in real-time forests of one million trees. However, the paper focusses on the performance of a hardware instancing approach for rendering large quantities of detailed tree meshes, and not necessarily with the representativeness on the placement of the trees. With advancement of real time rendering and game engines like Unity and Unreal Engine (UE), the process of visualizing 3D city models became more efficient and accessible, moving from 3D City models to 3D City visualizations. Still, developments are needed to automatically generate realistic visualizations of vegetation of large areas, replicable for different areas in a country and usable for user collaboration and co-creation in planning processes of the built environment.

This paper presents the early-stage development of a DT in VR aiming for civic engagement in the planning of Landvetter Södra, one of Western Sweden's largest new urban development located in an area that is forest today. The forest is an appreciated recreation area for people living nearby. Therefore, it is important for the developer both to be able to communicate how the new development will affect the forest and to allow for feedback from the citizen.

1.2 Aim and scope

The study aims to create an automated, procedural workflow to generate DT models and visualize large-scale VR data with a focus on existing green structures to provide a basis for participatory approaches. The following research questions are explored: How to can the natural and built environment be procedurally visualized on the site using real-world data? How can the impact of the development on the natural surroundings with a focus on green structures be suitable communicated and how is it perceived?

A VR application is developed and tested with a focus on realistic, immersive visualizations of green structures with focus on vegetation and efforts on realistic representation and placement of different types of trees and bushes. The VR application is designed for a specific location and development case; however, the ambition is to prepare a workflow and prototype that can be transferred to other locations. This paper describes the workflow, the user tests, and learnings from the user tests. The project is also linked to the Swedish national competence centre Digital Twin Cities Centre (DTCC, dtcc.chalmers.se), enabling connection to a DT platform and potential future integration with other projects and user interfaces. There is no consensus on a definition of what constitutes a DT for a city or urban environment. However, a DT is increasingly being used to describe something that is more than a 3D city model including, e.g., semantic data, real-time sensor data, physical models, and simulations (Ketzler et al., 2020). Our study is heading integration into a DT platform. Therefore, we use the term DT.

2. METHODS

In an iterative process, two versions of a first VR prototype for vegetation were developed in close cooperation with the urban developer to ensure relevance of the content and to prepare for future applications in participatory processes. For the prototype, a new procedural workflow was developed to generate DT models and to enable visualization of large-scale data in VR environment in an automated way. The versions of the prototype were evaluated in two user tests.

2.1 Development of workflow

The workflow consists of two parts, a) world creation and b) data visualization and VR integration. The data workflow is summarized in Figure 1.

For the world creation, available GIS data from the Swedish Mapping, Cadastral and Land Registration Authority (Lantmäteriet) were used to generate a 3D virtual city model (VCM). Data from other national data providers such as the

Swedish Transport Administration (Trafikverket) and Swedish Forest Agency (Skogsstyrelsen) were used to procedurally build the natural and built environment of the selected region.

The primary components chosen for the natural environment are geographical features focusing on vegetation ecosystems, whereas the built environment consists primarily of buildings and roads. This workflow can later be extended to the built environment's finer details, such as road markings, traffic signage, and street furniture. At this stage, the project aimed to produce a scalable pipeline to explore the software and methods for automatically generating and visualizing large-scale data integrated into VR.

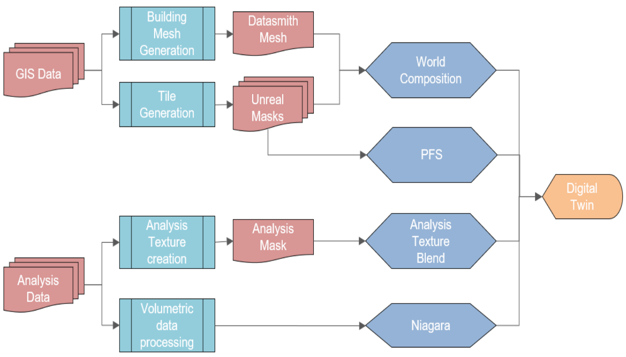

Figure 1. Data pipeline for the procedural digital twin generation

For the data integration, the platform Feature Manipulation Engine (FME) was used to pre-process the data before feeding them into the VR application. The application is based on a collaborative viewer built in the real-time 3D creation tool Unreal Engine (UE).

For the terrain, the Digital Terrain Model (DTM) from Lantmäteriet is used with a two square meter-per-pixel resolution consisting of 6.25 square kilometres per tile. A post-processing step is introduced to ensure that the workflow is procedural, which re-samples the incoming DTM raster to a pre-determined cell spacing. The DTM is then combined into a single raster and further re-tiled into specific dimensions to ensure the maximum area while minimizing the number of tiles in UE. The final step in creating the terrain tiles is to ensure the tiles are systematically named for UE to identify the tiling layout. Once the terrain tiles are generated, they can be imported into the UE using the World Composition feature.

Road data are provided by Lantmäteriet and Trafikverket as road centre-line polygonal vector data. The vector data consists of twenty road classes such as tunnels, thoroughfares, public roads, roads under construction, and a range of road widths. We simplified the roads into four classes and assigned fixed road widths to each class. The centre-line data is then post-processed to form landscape masks for UE. A spatial buffer across all centre-line polygons per the road class is performed and the resulting polygon offset is dissolved to form the road boundary regions. Then, the road tiles are rasterized, tiled, and renamed.

For the vegetation, the focus of this study, efforts focused on the vegetation such as realistic representation and placement of different types of trees as well as bushes. Other natural elements (water, terrain, stones) were represented using a lower level of detail (material shaders). Lantmäteriet provides data for land-use classification in form of vector polygons. The data consists of 13 natural and human-made land-use classes such as water (lakes and large watercourses), different types of built-up areas, land areas, and forests. For simplicity, we reduced the land-use classes to six - water, forest, farm, open land, road, and urban. For each of the land-use classes, the vector data was first rasterized with binary cell values (0 representing the absence of land-use class and 1 representing its presence) to the predefined cell-spacing as the terrain tiles.

The final step in preparing the landscape tiles ensures that the different layers are incorporated into a single, seamless composition. Two issues are addressed. First, the land-use boundaries are generated irrespective of the road networks; this causes an overlap of binary raster values at the intersection of a land-use class and a road segment. Second, the process of rasterizing vector data results in a steep drop in the cell values; this presents pixelated boundaries at the edge of the boundaries.

In the next step, raster data are subtracted for the land-use layers with the road network to avoid any overlap; then, a raster convolution filter across the layers is applied using the Gaussian function, which ensures a gradual falloff in values at the boundaries of the layers. To complete the integration process, the terrain mask is imported into the UE using the World Composition feature, the scaling factors in the x, y, and z dimensions are provided, and the subsequent landscape masks to a procedural landscape material are assigned (Figure 2).

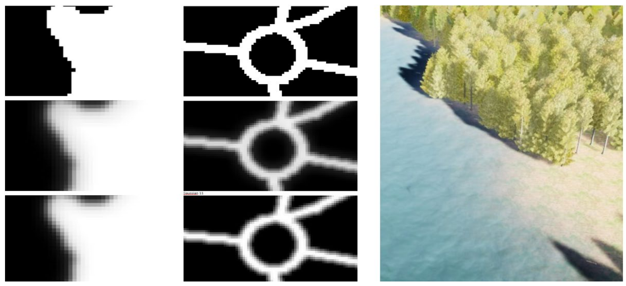

Figure 2. Results of convolution filters on the landscape masks (Left, Middle). Result of convolution on landscape masks, Unreal Engine vegetation generated through the Procedural Foliage Generator (Right)

The building meshes are generated using two data layers provided by Lantmäteriet, the building footprints and a LiDAR point cloud. The building's height is determined by calculating the median values of points in the z dimension above a building's footprint. A LOD1, building mesh is then generated by extruding the building footprints to their respective heights. Buildings are repositioned in the z dimension to meet the terrain, and a DataSmith file is generated from the building meshes and imported into UE (Figure 3).

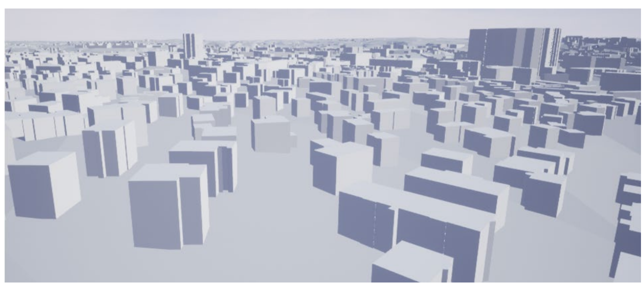

Figure 3. Level of Detail 1 meshes within Unreal Engine

Some issues were encountered in geolocating the buildings procedurally within the required tolerances. The building meshes have a slight affine transformation in the x, y, and z directions which is currently addressed manually. This issue will be addressed in future iterations of the project.

The data visualization is primarily concerned with visualizing large-scale data while maintaining the workflow's procedural nature and compatibility with the digital environment.

2.2 Prototype development

The VR application was prepared for the specific geographical location, the development area and the nearby environment (9km x 8km). However, the orientation abilities were less important than the experience of the representations of the vegetation in the user tests.

Once the landscape tiles were procedurally generated from step 2.1, they are imported into a modified VR UE template[1]. The UE template is based on the default Unreal Engine VR template that provides the basic requirements to generate a VR application. The default template includes the logic for users to teleport and input actions such as grabbing and attaching items to their hands. To optimize the viewing experience in the VR environment based on the distance the viewer is from different objects, the LOD switching feature of UE was used. The LOD switching makes efficient use of the computer hardware by swaping the meshes for the trees and other high fidelity meshes in areas close to the user with lower resolution meshes and finally a 2D silhouette when the user is significantly far away. A welcome screen was added to enhance the user experience where users can assign a user name and enter the application. The user interface and interaction logic were designed using Blueprints, the visual programming interface for UE.

In the VR environment, users are given the ability to move or remove existing buildings represented as simplified 3D cubes to indicate placements. Roads are only visible in a bird's-eye view. The buildings represent a collection of existing and proposed buildings. Basic information was added to the buildings, such as the type of building and floor area (Figure 4). As the development area is in the forest, it was important to combine and switch between the bird's-eye view to support user orientation in relation to well-known points of interest and a pedestrian view to experience the local area. Figures 5 and 6 represent examples from a bird's-eye view. Figures 7 and 8 illustrate the result from a pedestrian view.

For the second user test, additional interactive features were added for users to move the proposed buildings, save images of interesting areas, and draw and comment in the virtual environment. Several locations of interest were saved as bookmarks to allow users to instantly navigate to different parts of the area. Users also have the ability to scale themselves from a range of 10:1 (ten times smaller than human scale) to 1:50 (fifty times larger than human-scale).

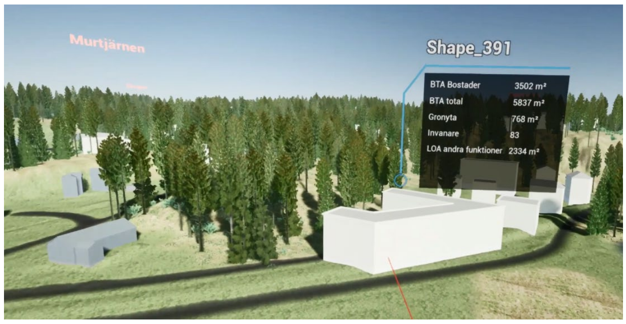

Figure 4. Buildings with information about size and use

Figure 5. Vegetation generated through the Procedural Mesh Generator. Bird's-eye view

Figure 6. Moving of buildings in the bird's-eye view

Figure 7. Vegetation generated through the UE Procedural Foliage Spawner. Pedestrian view

[1]https://docs.unrealengine.com/4.27/en-US/Resources/Templates/VRTemplate/

Figure 8. Vegetation details generated through the UE Procedural Foliage Spawner. Pedestrian view

2.3 User tests

Two user tests were carried out in November 2021. The first user test was part of a workshop within a course about DTs for practitioners having different backgrounds (architects, software developers, consultants, urban developers, municipal officers), with interest in DTs and curiosity about VR but little to no experience in using it. Oculus Quest VR headsets were used. For the first test, only navigation functions were enabled in the VR application, and participants could explore and navigate the scene. The second user test was carried out with school children. Here, in the VR, interactive functions were enabled, and the participants were able to explore, navigate, and interact with the scene. Table 1 summarizes participants' background and the enabled VR functionalities, and Figure 9 and 10 show examples of the functionalities.

In both tests, the researchers observed the participants (movement, actions, speaking out loud) and notes and photographs were taken by one of the researchers. After testing the VR in the first user test, short unstructured, reflective interviews were conducted with a focus on the experience of the vegetation. In the second user test, a more general group reflection was carried out. The interviews and group reflections were documented by taking notes. The evaluation focused on the perception of the vegetation, but also comments on the general perception of the VR environment, interaction, and navigation were noted.

UT	#	Participants' background	VR functionalities
1	9	Built environment professionals, interest in DT, not experienced in using VR	Walk (jump) around, Fly around, Jump to different places, Switch bird's-eye and pedestrian view
2	9	School children, age 15	Walk (jump) around, Fly around, Jump to different places, Switch bird's-eye and pedestrian view, Change scale, Draw lines, Move buildings, Take photographs

Table 1. Participants and enabled VR functionalities in the user tests. UT = number of user test, # = number of participants in user test.

In the beginning of both user tests, the participants were introduced to the VR application through a PowerPoint presentation with information about the content of the application and the focus on vegetation. In the first test, also the data model and workflow behind the VR application were explained. After that, the participants could test the VR supported by the researchers, Figure 11. In the second test, the school children focused on getting familiar with the navigation and interaction functions such as placement of new activities and buildings in the area. This was connected to a school project work on sustainable urban development together with the urban developer. In preparation for the user test and to understand values of vegetation, the school children had carried out a mini survey. They had asked residents living close to nature and in similar areas as the one to be developed, if they care about the green areas where they live and the reasons for why or why not. Furthermore, they had asked what would motivate people to move to a new city and what activities they would like to have in a new city, etc. Thus, building on this survey, the second user test was more playful. The children started to draw where they wanted to have certain types of buildings, for example an ice hockey rink and a shopping mall. In general, the children mainly tested and played with the interactive functionalities.

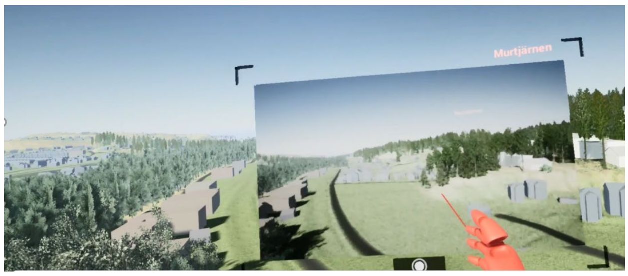

Figure 9. One of the interactive functionalities in the VR application was "taking photographs"

Figure 10. Viewer menu for selection of functionalities

Figure 11. Testing of VR. After a short introduction to the VR application and focus on vegetation, the participants tested the VR supported by a researcher

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-4-W5-2022-189-2022

3. RESULTS

Results concern the perception of the vegetation but also elements such as buildings, the VR environment including navigation and interaction, ideas for content development of the VR application to make it more relevant for different stakeholders and the planned civic engagement process, and more general other potential use cases and data pipeline.

3.1 Realistic vegetation is appreciated

The practitioners appreciated the appearance of the green spaces and the realistic presentation of the vegetation – trees, gras, bushes – was well perceived Many participants mentioned "beautiful", "feels authentic", and described it as immersive through the high level of detail. In particular, the movement of the trees in the wind was described as creating a good atmosphere together with nice weather in the virtual environment. Further statements included "very realistic and magic", "you can jump down to grass level, you are a grasshopper and at the same time fly around in the air and look at the scene". Another participant felt that the VR application was a very good tool for vegetation and liked the richness of details while the environment felt "stable" at the same time. For one of the participants, however, the high level of detail of the nature in the hilly environment was perceived as "scary". For the school children, many of them with considerable experience from computer gaming, the reactions on the realism were more moderate and not really commented on.

3.2 Buildings and related information

The focus of the prototype was on procedurally created vegetation with real, geolocated position of the trees and realism and not on buildings. Still, buildings were included to prepare for the planned citizen participation and engagement process. Thus, not surprisingly, the lack of more detailed (material representative) texture of the buildings was reacted on (white blocks), "looks like concrete blocks" was mentioned. It was suggested that it would be better to write sustainable buildings or at least to show a materiality. Generally, it was appreciated to get some information about the buildings when clicking at the blocks and to have the ability to distinguish existing buildings from new ones. Building-related information to add could be occupancy and how many people live in an area or are expected to live there.

In the user test with the enabled interaction mode, i.e., with the school children, there was a request for a library with different buildings to choose from and the option to place them.

3.3 Navigation and interaction

The practitioners asked for improved orientation, the marking of points of interest (center, home, etc.) and more details so one would know or recognize where one is. The addition of orthophotos was suggested for better orientation in the area when zooming out. As the prototypes did focus more on the perception of the realism and not orientation, this was an expected comment it will be taken care of in the coming development of the prototype.

The school children asked for increased interaction when it comes to the vegetation, they wanted to be able to place more plants and trees and remove trees. They also wanted to "furnish" the houses, work with the facades, add roads and paths, and more activities.

Walking around in the VR application was perceived as a bit bumpy. This is related to the current navigation system which requires users to point and click at a destination to move to them in small jumps.

For participants who were not familiar with VR, i.e., almost all in the first user test, the starting process to get familiar with the VR equipment and functionalities was time consuming, and the researchers needed to help the participants during the whole test. The school children, in contrary, needed only a short introduction to the application by the researchers and could then play around independently. The children also explained and helped each other when problems occurred.

3.4 Ideas for future content development and use cases

Several potential future use cases were discussed during the user tests, such as understanding and balancing construction of new buildings and the city whilst preserving or relating to the existing environment. "Which places should be preserved?" "What would the area look like without the trees?" Or "How will the future area look like?" Unfortunately, this was not possible yet in our VR scene, and some participants expressed disappointment about that.

Different potential scenarios were proposed. Construction companies could explore densities of buildings in an area, place as many apartments/buildings as allowed to build in the area. Storytelling was mentioned, to select and show personal stories, such as how it would feel to go to school, go shopping etc. in planned development areas. Visualization could also be linked to carbon footprints related to removing trees and how it changes for different scenarios. Furthermore, prediction analysis was mentioned to be able to calculate and show the school capacity and the needs of a neighborhood. Other scenarios to test could be to explore how much parking is needed and what would different numbers mean for the development of the area.

Some participants mentioned that it would be nice to integrate more layers of senses; for example, sound or noise would provide an added value and better communicate how it would feel to be at a certain place.

3.5 Architects as potential user group

The VR application has been developed for future civic engagement processes. However, several of the participants of the first user test, professionals with different backgrounds, and especially the architects could see other potential use of the VR application. Often, static images on pdf files are used for communication of design proposals with the client. The rich level of detail in an immersive environment conveys a better feeling of the future places and could support their communication with clients. VR is interactive, and one can move around, make changes immediately so that clients might feel more involved in the process and the architects get help in augmenting solutions. Realistic VR can also support the architect's own design process by visualizing the potential consequences of different design solutions.

3.6 Workflow

As the first user test was carried out with professionals in the built environment field, also technical questions were asked, and comments were made about software, data format, standardization, easiness, and speed of creating the models. One participant highlighted that in VR, the visualizations can be more realistic than visualizations that use traditional 3D GIS data, which are usually used in the municipalities for development projects. Another participant was impressed by the fact that the procedural flow was only built on data from Lantmäteriet. Furthermore, it was mentioned that real-time data would be interesting to integrate.

4. DISCUSSION AND CONCLUSION

In this study, an early-stage VR prototype for representation and visualization of large-scale vegetation to be integrated in a DT has been developed and tested in two user tests. The VR application aims to support civic engagement, i.e., participation and co-creation processes, in the planning of a new urban development located in an area that is forest today. For this, a novel data pipeline and workflow has been created that can procedurally generate realistic, large-scale visualizations of vegetation with geo-located placements of trees and bushes based on real world data, and scalable to any location. The user test contributed to evaluate the perception of the vegetation in the VR application but also to explore future uses and developments of the application.

Compared to existing studies of VR in participatory urban development processes, which usually deal with transformation of existing built environments such as densification or redevelopment of places (e.g., Fares et al., 2018; van Leeuwen et al., 2018; Dembski et al., 2020; West et al., 2019), our study has the development of a large-scale are of virgin land with forest as a starting point. Thus, it adds a new application case for VR in participatory urban development processes. In such development processes it is important to be able to communicate with the citizen avoiding misunderstanding, which is challenging when it comes to large scale areas and partly inaccessible areas such as forests. Recognizability is one of the keys and VR applications for large-scale forest scenes with realism of trees are necessary. In line with previous research, we have shown that large-scale forest scenes can be rendered with high realism (Bao et al., 2012) using different LODs and view-dependent navigation to handle the complexity of the forest; but our study also handles representativeness on the placement of the trees.

Interaction in VR application is an important aspect in participatory processes, particularly when aiming at co-creation. Interaction was generally appreciated in our user tests, but there are several functionalities that need to be added for more efficient co-creation processes when it comes to the vegetation such as the possibility to remove existing trees and place more plants and other trees.

From a user perspective, the long starting process for the users who are not familiar with VR was seen as a drawback. It might be easier on a traditional computer using a mouse and a keyboard. Also, if you are not a regular user of VR, you need an introduction every time; the variety of different systems does not make it easier. It would be beneficial with a standardized user experience and to always have the same type of joystick or buttons. Walking in VR needs to be smoother; currently, the navigation system requires users to point and click at a destination to move them in small jumps.

The overall results show that the workflow is effective, and the users appreciated representations of vegetation in VR environments in both user tests. Based on the workflow, similar scenes can now be created for any location in Sweden. Future development needs to concentrate on the refinement of buildings and the information displayed along with them. Higher LOD models can be integrated into the procedural workflow when they are made available through other DT projects.

By using procedural workflows, the ability to generate DT becomes more readily available to stakeholders that would like to engage in discussion and collaboration with the residents. Virtual environments are a promising medium to communicate intangible aspects of the built environment like green spaces. They also allow users to communicate how these spaces make them feel. However, developers of DTs face a challenge in balancing the LOD in their models while clearly communicating how representative the virtual environments are but also to overcome technical barriers of VR. The same workflow could be used in different user interfaces and, by that, “talk” to people with different communication skills. For example, the VR application could be combined with visualizations on a touch table, projections on a physical 3D model or desktop visualization all carefully integrated in a well-designed planning and co-creation process. Existing studies have different views on the topic, some do not see any difference in the engagement with decision making (Van Leeuwen et al., 2018), others excluded some age groups (elderly) due to Internet concern (Fares et al., 2018), and even others pointed at the potentials to include citizens who otherwise are not very active in urban planning and design processes such as children, teenager, residents with migrant background or language barriers (Dembski et al., 2020). In our study, we could see a difference in the easiness to handle VR technology, where the adults were struggling more than school children. For the planned participatory processes of the new development in the forest with the citizens, it is therefore important to be as inclusive as possible, i.e., to be aware of age groups’ different needs.

Currently, the DT model consists of an early-stage development plan provided by the developer. This scenario shows the functions of the proposed buildings located alongside the existing forest. We used this scenario to explore and develop methods to quickly develop procedural virtual DT models and test them with user studies. In future steps, we plan to allow users to switch between multiple development scenarios and view the existing nature without any development for reference. Allowing users to interact with the virtual environment simultaneously using multiple VR headsets can be beneficial to gathering collective feedback and contribute to a collaborative planning process. For first-time VR users, the experience can often be disorienting, and it can take a while to get used to the controls. We plan to design an orientation exercise prior to exploring the virtual environment to address this. Other features to help users orient themselves in the virtual environment like a keymap and direction pointer will also be explored. Furthermore, sound will be added to the VR experience. This was wished by participants in the user test and Lindquist et al. (2020) showed that ambient and realistic sounds increase perceived realism for the perception of virtual green spaces.

Limitations of our study are the early stage of the VR prototype and the explorative nature of the user tests. The two tests evaluated two slightly different versions of the prototype and the participants comprised different age groups (adults/ professionals and school children). Nevertheless, the results are valuable for further development of the prototype and design of the participatory process. The data pipeline for the procedural DT generation is applicable to other locations.

Finally, the developed VR application for realistic visualizations of large-scale vegetation scenes with representative, real-world location of the trees based on a novel procedural workflow for DT generation is a promising approach to support future engagement of citizens in urban development processes, especially when the new developments are built in nature or forest areas.

ETHICAL STATEMENT

Participants in the user tests were asked for consent. In the first user test, the participants signed a confirmation to be filmed and observed by the researchers. In the second user test, the parents agreed with the teacher that the school children can participate in the user test.

ACKNOWLEDGEMENTS

This work is part of the Digital Twin Cities Centre supported by Sweden's Innovation Agency Vinnova under Grant No. 2019-00041 and connected to the Milestone Project Twinable. The authors especially would like to thank Emanuel Björsell at AFRY for the support of the VR prototype development, Orfeas Eleftheriou at Applied Mathematics and Statistics, Department of Mathematical Sciences, Chalmers University of Technology, for support with Unreal Engine integration, the participants in the user tests, and the developer Landvetter Södra Utveckling AB for providing the case area and valuable contribution to the content development of the VR application.

REFERENCES

Alomia, G., Luo, X., Zúñiga, C., Cadavid, A.N., Lozano-Garzón, C., 2019. Automatic 3D Urban Installation Generation in Virtual Cities. *Int. Conf. on Virtual Reality and Visualization,* ICVRV, 217–222.

Bao, G., Li, H., Zhang, X., Dong, W., 2012. Large-scale forest rendering: Real-time, realistic, and progressive. *Computers & Graphics*, 36(3), 140-151.

Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., Yamu, C., 2020. Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany. *Sustainability*, 12(6), 2307. doi.org/10.3390/su12062307

Gil, J., 2020. City information modelling: A conceptual framework for research and practice in digital urban planning. *Built Environment*, 46(4), 501-527.

Huang, J., Lucash, M.S., Simpson, M.B., Helgeson, C., Klippel, A., 2019. Visualizing natural environments from data in virtual reality: Combining realism and uncertainty. *IEEE Conf. on Virtual Reality and 3D User Interfaces* (VR), 1485-1488.

Fares, F., Taha, D.S., EL Sayad, Z.T., 2018. Achieving public participation in inaccessible areas using virtual reality a case study of Beit Hanoun–Gaza–Palestine. *Alexandria Engineering Journal*, 57(3), 1821–1828. doi.org/10.1016/J.AEJ.2017.07.010

Fegert, J., Pfeiffer, J., Golubyeva, A., Pfeiffer-Leßmann, N., Hariharan, A., Renner, P., Pfeiffer, T., Hefke, M., Straub, T., Weinhardt, C., 2019. Take Part Prototype: Creating New Ways of Participation Through Augmented and Virtual Reality. *29th Workshop on Information Technologies and Systems*, WITS, Munich, Germany.

Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., Logg, A., 2020. Digital twins for cities: A state of the art review. *Built Environment*, 46(4), 547-573.

Lindquist, M., Maxim, B., Proctor, J., Dolins, F., 2020. The effect of audio fidelity and virtual reality on the perception of virtual greenspace. *Landscape and Urban Planning*, 202, 103884. doi.org/10.1016/j.landurbplan.2020.103884

Portman, M.E., Natapov, A., Fisher-Gewirtzman, D., 2015. To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning. *Computers, Environment and Urban Systems*, 54, 376–384. doi.org/10.1016/J.COMPENVURBSYS.2015.05.001

Prechtel, N., 2015. On strategies and automation in upgrading 2D to 3D landscape representations. *Cartography and Geographic Information Science*, 42(3), 244–258.

Rajpriya, N.R., Vyas, A., Sharma, S.A., 2014. Generation of 3D Model for Urban area using Ikonos and Cartosat-1 Satellite Imageries with RS and GIS Techniques. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci*., 40(8), 899.

Semmo, A., Trapp, M., Kyprianidis, J.E., Döllner, J., 2012. Interactive Visualization of Generalized Virtual 3D City Models Using Level-of-Abstraction Transitions. *EuroVis, Computer Graphics Forum 31*, 885–894. doi:10.1111/j.1467-8659.2012.03081.x.

Shan, P., Sun, W., 2021. Research on landscape design system based on 3D virtual reality and image processing technology. *Ecological Informatics*, 63, 101287. doi.org/10.1016/j.ecoinf.2021.101287

Stoter, J., Ho, S., Biljecki, F., 2019. Considerations for a contemporary 3D cadastre for our times. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci*, 42, 81–88.

Van Leeuwen, J.P., Hermans, K., Jylhä, A., Quanjer, A.J., Nijman, H., 2018. Effectiveness of virtual reality in participatory urban planning. *ACM Int. Conf. Proceeding Series*, 128–136. doi.org/10.1145/3284389.3284491

West, M., Yildirim, O., Harte, A.E., Ramram, A., Fleury, N. W., Carabias-Hütter, V., 2019. Enhancing citizen participation through serious games in virtual reality. *24th Int. Conf.e on Urban Planning, Regional Development and Information Society*, pp. 881–888.

Zhang, Z., Luo, X., Salazar Vaca, M.G., Espinoza Castro D.A., Chen, Y., 2017. Vegetation Rendering Optimization for Virtual Reality Systems. *Int. Conf. on Virtual Reality and Visualization* (ICVRV), pp. 397-399, doi: 10.1109/ICVRV.2017.00094