Workshop on Visualisation in Environmental Sciences (EnvirVis) (2023)
S. Dutta, K. Feige, K. Rink, and D. Zeckzer (Editors)

Potential of 3D Visualisation and VR as Boundary Object for Redesigning Green Infrastructure - a Case Study

C. Helbig[1] and J. Pößneck[1] and D. Hertel [1] and Ö. O. Sen [2]

[1]Department of Urban and Environmental Sociology, Helmholtz Centre for Environmental Research—UFZ, Leipzig, Germany
[2]Department of Environmental Informatics, Helmholtz Centre for Environmental Research—UFZ, Leipzig, Germany

Abstract

Faced with most various challenges (e.g. climate change, biodiversity loss, population growth) that will affect people's future lives in cities, analysis, planning and communication tools that bring together data from different areas and thus create a holistic picture of the environment are needed. This includes data with a socio-economic background as well as data on urban structure, vegetation, climate data and many others. The integration of heterogeneous data and their visualisation are part of the presented case study. The aim was to create a boundary object that facilitates the communication between actors with different social and disciplinary backgrounds in the process of redesigning green infrastructure. 3D visualisation and virtual reality were demonstrated to various stakeholders in transfer events. They confirmed the visualisation's potential to serve as a boundary object. It represents an appropriate group-specific communication tool for a thematic Digital Twin that supports the transformation to a sustainable and resilient city in light of future changes.

1. Introduction

In the context of the climate crisis, the potential of green infrastructure (GI) is being discussed due to its multi-functionality and ability to improve the urban environment [MA14, Lin17], although it can be viewed critically [DPD*22]. However, the positive influence of GI on urban drainage resilience [RFB*21], urban air quality [HAM20] and urban heat [HS19, WZS22] has been demonstrated in many studies.

The number and intensity of extreme events such as heat waves will increase in future [FBS*12]. First signs pointing to such a development, especially after 1997, were analysed by e.g.: [CJS15, MCM*17]. The (re)design of GI plays an important role in making cities resilient towards extreme events and promoting sustainable urban development. GI is embedded in a complex urban system and interacts with the surrounding environment demanding for a more comprehensive perspective for the evaluation of GI potentials in light of the climate crisis. Thus, adequately addressing the complexity of the urban environment requires an interdisciplinary perspective and the involvement of different actors. In this paper, we present the approach of using 3D visualisation as a boundary object to

1. analyse complex, heterogeneous data from different disciplines and
2. present it on a PC or in an immersive virtual reality (VR) environment to bridge communication boundaries in the context of urban planning and GI redesign.

In the context of this paper, by 3D visualisation we mean the spatial representation of data such as buildings and vegetation using 3D models, as well as the representation of abstract data such as wind flow using streamlines. This 3D visualisation can be projected stereoscopic using a virtual reality environment.

2. Methods

2.1. Conceptual Framework

To cope with changing environmental conditions as a result of climate change, targeted and effective adaptation measures are necessary. Existing tools and guidelines to support municipalities with the implementation of climate adaptation strategies are often rather generalizing and abstract without concrete examples of application such as the redesign of GI. Furthermore, usually only individual kinds of data are considered (e.g. modelling, indicator development or socio-demographic data) and no systemic data integration that combines data outputs from various methodological and professional approaches [RSL*20]. However, this cannot meet the complexity of the urban environment. Integrated assessments of the impacts of extreme events [NKB*22] or an interdisciplinary approach, as represented by the concept of "Planetary Health", can be helpful in addressing these challenges. [FBTa21] unite the following four thematic areas in their Planetary Health model that need to be considered when dealing with environmental stressors: physical/built environment, socio-economic well-being, environment and ecology, and human health. The result of such an integrative and interdisciplinary approach is a large amount and complexity of very different data sets. In order to provide added value for the urban

DOI: 10.2312/envirvis.20231105

planning practice and to overcome barriers between these thematic areas, the interplay and combined effects on climate-adapted planning strategies need to be appropriately processed for and communicated to various stakeholders. This involves, e.g., planning authorities, the residents, housing companies, civil society initiatives, and the scientific community. All of them have different interests, needs and levels of knowledge. 3D visualisations and VR can be used as boundary objects to overcome communication challenges, bridge boundaries between these diverse stakeholders, and act as a synthesis channel (as thematic Digital Twin) for cross-sectoral concepts like "Planetary Health" that help coping with future challenges (Fig. 1).

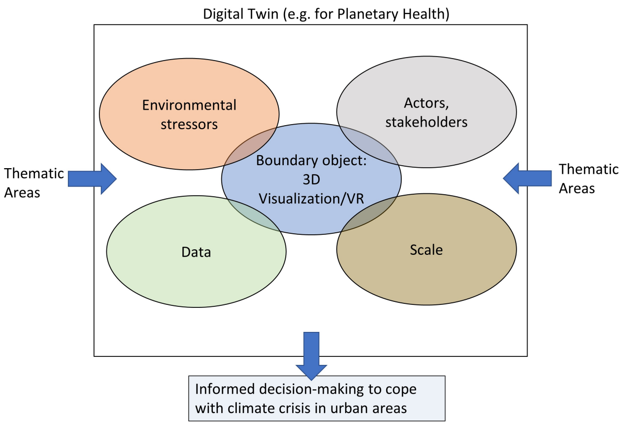

Figure 1: *Illustration of the conceptual framework*

We interpret a Digital Twin as a virtual representation of a system (e.g., Planetary Health in urban areas) that involves the impact chain for a given challenge (e.g., heat stress) in order to enable well informed decision-making in light of future changes through the climate crisis. The boundary object acts as a melting pot for the different data sets and user groups to represent a platform (communication tool) for this virtual representation. Following Star and Griesemer ([SG89], p. 393), we understand the 3D visualisation as a specific tool that can be recognised and used by different actors, even if the information presented will be interpreted and adapted differently, depending on the disciplinary background as well as local requirements and individual needs.

Our approach is to use 3D visualisation as a boundary object and thus support communication between different actors involved in the discussions about redesigning GI. 3D visualisations and VR are increasingly used as a communication instrument in urban planning processes [MLB*21, NvE*21, Pei21, ZZ21]. [BTSW16] identified five challenges for implementing visualisation tools, including the "challenge of integrating data" and the "challenge of representing data". The first, in addition to the amount of data, also refers to the integration of qualitative / social / "soft" values and quantitative / physical / "hard" parameters. The second challenge appears for instance in the way of switching seamlessly between different levels of detail. [HDB*17] also identified challenges concerning the development of suitable visual exploration concepts and methods as well as pointed out the need for implementing effective and tailored tools that are intuitive and provide adequate interaction methods. Besides technical questions, there are also psychological barriers [Wil20, HDB*17] about integrating such advanced technologies in daily workflows of relevant stakeholders. They are not trained in using these technologies. More efforts in communicating the benefits, research about possible use cases, co-designing tools according to user needs or developing guidelines for good practices are required.

Based on the above, we address the following questions:

- To what extent can 3D visualisation / VR be used as a boundary object to create a thematic Digital Twin on the basis of which decisions can be supported?
- What is the potential of 3D visualisation / VR as a communication tool for GI redesign?
- How can data of different characteristics be integrated and represented in 3D space?
- How can usability be realised across different user groups?

2.2. Case Study

To develop and test 3D visualisation and VR as a boundary object for integrating different data sets and bridging boundaries between stakeholders as well as disciplines, we conducted a case study in the large panel housing estate Leipzig-Grünau, at the western fringe of the City of Leipzig. We selected this area because we can build on experiences and extensive data from previous studies at the Helmholtz Centre for Environmental Research - UFZ, Leipzig. The development of the entire housing estate has been investigated since 1979 within the framework of a sociological long-term study addressing, among other topics, residential satisfaction, environmental perception and the socio-demographic characteristics of the residents. A comprehensive and unique data set is available from eleven resident surveys. The most recent one took place in 2020 [KP21].

As part of the international and interdisciplinary project uVITAL ("User-Valued Innovations for Social Housing Upgrading through Trans-Atlantic Living Labs", funded by the Federal Ministry of Education and Research – BMBF (DLR-PT); funding number: 01UG2025), we focused on a neighbourhood in the south-eastern corner of the district Grünau-North (see Fig. 2). The initial research was on housing upgrading, but it has been extended to redesigning GI.

In the specific case study area, there are five prefabricated panel buildings of nine storeys each. Four of them are rented out by the municipal housing company. One is used as a student residence. In between, there are green spaces with meadows and trees, and paths that connect the buildings. There is also an area where people can dry their clothes. There used to be a playground, but the equipment has been removed. In the near vicinity of the buildings, there are few seating facilities, only three smeared benches, that are difficult to access due to tripping hazards. This is important to mention because most of the residents in this area are elderly people who often live alone in a one- or two-room apartment. Some of them are with reduced mobility and have to use a wheelchair, walker or other

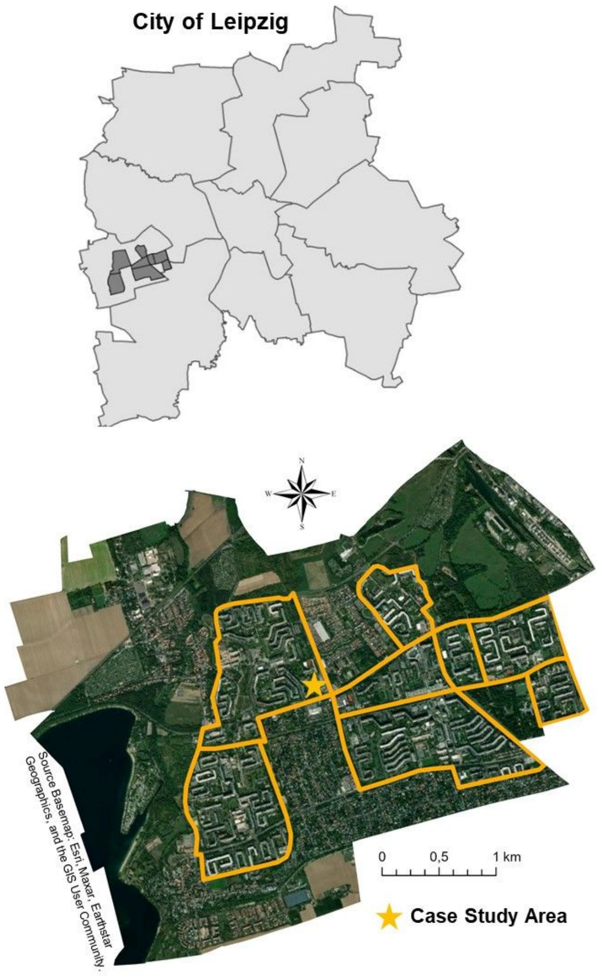

Figure 2: *Location of the large panel housing estate Leipzig-Grünau and the specific case study area in Grünau-North*

walking aids. As part of the uVITAL project, we conducted interviews with, e.g., residents, representatives of the housing company and the municipality. The idea was to use the collaborative redesign of the green spaces through 3D visualisations and VR as a means to encourage the residents to leave their apartments and to promote social cohesion in the neighbourhood.

Additionally, in the context of the project "Hitzestress" ("Heat Stress", funded by the German Federal Environmental Foundation - DBU; funding number: 37993/01), a state-of-the art urban climate model was applied for this area and respective micro-meteorological simulations were conducted. The input data (e.g. 3D buildings, streets, vegetation etc.) have already been processed for the whole city [HZS22], including Grünau-North. For the simulation of the local thermal conditions, we selected the PALM-4U model (v6.0, 2018) with a horizontal grid number of 750 x 750 and a grid size of 2 x 2 m. PALM-4U is a non-hydrostatic large eddy simulation (LES) tool that can be applied in complex environments (3D) to calculate turbulent flow fields with a high resolution of up to a few metres. The LES-approach combines high precision with high computing performance and because of a broad spectrum of potential applications this kind of urban climate modelling gains increasing importance for the scientific community and also for practitioners. The model was used with static drivers that incorporate terrain height (from digital elevation model), building height (from 3D city model of Leipzig), building ID (3D city model), building type (3D city model), vegetation type (from 2D street trees, open street map, ATKIS data), water type (open street map data), pavement type (open street map data) and soil type (BÜK200 - "Bodenübersichtskarte" Germany, scaling 1:200000). The meteorological boundary conditions were taken from a measurement site of the German Weather Service at Leipzig-Halle airport and a weather station at the University of Leipzig (Institute for Meteorology).

The objective was to integrate and represent these different kinds of data sets in 3D space. However, due to the Covid-19 pandemic and the resulting delays in the (uVITAL) project process, extensive formal user evaluation tests were not possible.

2.3. Technical Implementation

For the implementation of the visualisation application [HPHS] we used the Unity game engine (Version 2019.4.19f1). Unity is a development environment for computer games and other interactive 3D graphics applications. Using Unity enables us to integrate heterogeneous data, combine methods of 3D visualisation and VR as well as to implement analysis methods and make them available via a user interface.

In the following chapter, we will go into more detail on aspects of data integration, the visualisation methods used, and the navigation and interaction functions provided.

2.3.1. Data Integration

In the application, data from very different sources, with distinctive characteristics, are included. They range from empirical data, to cartographic data, to simulated data. The individual data sets and their integration are briefly described in this section.

The **socio-economic data** from the municipal statistics at the level of statistical blocks were provided by the Office for Statistics and Elections of the City of Leipzig (status 31.12.2021). This includes information on the residents of the respective block such as age group, gender, marital status and proportion of migrants. The **questionnaire data** were collected during a resident survey in June and July 2020 as part of the sociological long-term study. It includes information on the residents such as age group, gender, household structure, educational qualification and employment status. They were also asked about their perception of extreme events and their attitude towards heat adaptation measures. Both, socio-economic and questionnaire data were available in table format and were converted into graphs. These were transformed to material textures in Unity and can thus be integrated into the scene.

Qualitative data were collected through interviews conducted as part of the uVITAL project. For instance, the use and the perception of the green spaces by the residents were discussed, as well as

Proceedings published by Eurographics - The European Association for Computer Graphics.

ownership and responsibilities, and questions about the concrete implementation of design options (including obstacles, legal requirements, etc.). Individual aspects of this have been considered in the creation of the design scenarios.

As part of the "Hitzestress" project, **urban climate simulations** were carried out in the case study area. The simulations were conducted by help of PALM-4U (see section 2.2) for 23.9.2010 since airborne thermal scans were available. As a result, the simulations provide hourly data on wind fields and PET (physiological equivalent temperature) values. The "PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed" [Hö99]. The simulation outcomes were visualised with ParaView [AGL05] and exported as an FBX file, which was then imported into Unity as a game object.

Data from the **urban climate analysis** of the City of Leipzig was integrated [BT21]. In the analysis, data were collected on the microclimate, the flow field and the heat stress of the people in Leipzig. On the basis of this data, 17 action plans were derived and spatially represented. The action plan maps show where a specific strategy can help to reduce the heat load prevailing in the block or in the street space. The data is available in the form of PDF maps. These were analysed and the respective status for all 17 action plans was determined for each building in the scene.

Orthographic photos were used as a basis in order to reproduce the development of the area as realistically as possible. In addition, several site visits took place, during which **sketches and photos** of the surroundings were made. Additional information was obtained from Google Earth. The orthographic photos are given as images and were transformed to material textures in Unity and can thus be integrated into the scene.

Unity offers the possibility to integrate **sound effects**. In order to not only be able to experience the visual aspects of different scenarios in comparison to the current situation in the area, a sound file with traffic noise was integrated into the scene. This additional audio stimulus is intended to allow for experiencing the difference between the scenario and the status quo even more intensively. It must be pointed out, that the sound is perceived equally strongly from all positions in the area. In order to achieve a more realistic integration of the sound-scape, a precise analysis of the location regarding shielding/reflection of sounds would have to be carried out and then integrated into the scene. The sound file was available in MP3 format and could thus be easily integrated into Unity.

A number of **3D models** (buildings, vegetation, streets, etc.) are needed to set up the scene. These were directly downloaded from the Unity Asset Store.

2.3.2. Visualisation Methods

The representation of the different data described in section 2.3.1 is done according to their characteristics with the help of 2D or 3D representatives in a Unity scene. **Real world objects** such as buildings, vegetation, infrastructure (streets / pathways / tram tracks), outdoor furniture, playground / play area, and parking areas with cars are represented by realistic 3D models. The positioning of these objects in the status quo scenario (see section 3.1) is based on the orthographic photos, the site inspection and information from Google Earth. When selecting 3D models in the Unity Asset Store, it is important to ensure that they are compatible with the corresponding version of Unity (2019) and that they have as few polygons as possible (especially for 3D models that appear several times in the scene). The richness of detail of a 3D model must always be weighed against its size in order to guarantee good performance of the scene. Unity supports the calculation and display of shadows of 3D models in the scene. For the representation of vegetation and with regard to the height of the buildings in the scene, the different shadow cast in the scenarios is very important. In an intuitive way, it represents coolness, especially if one set the scenario on a hot summer day.

In addition to the real world objects, the following **abstract objects** are added to the scene (see Fig. 3): streamlines (representing wind), plane with colour coding (representing PET values), coloured boxes around the buildings (representing the status of action plan of urban climate analysis), a cube with corresponding symbol (representing use of buildings, e.g. student residence, school, elderly care), and info points for additional information (see next paragraph).

In order to be able to integrate **2D data** such as socio-economic statistics and questionnaire data as well as photos into the scene, these are used as elements of the user interface.

2.3.3. Navigation and Interaction

When it comes to complex, heterogeneous data, Shneiderman's mantra "overview first, zoom and filter, details on demand" is still relevant [NS00]. This concept is particularly suitable when there are different user groups. In the developed application, a navigation bar gives the possibility to show and hide different data sets. In this way, the view can be adapted according to the question to be addressed. Thus, the complexity is reduced and details are only shown when necessary.

The different **scenarios** (Status Quo, Scenario 1, Scenario 2, for details see section 3.1) that can be displayed are selected via a drop-down menu. Likewise, the **simulation results** for wind and PET can be shown through such a menu. In addition, it is possible to select individual time steps. The relevance of individual measures of the **action map** (M01 Shading of buildings, M02 Green roofs, M03 Energetic renovation, M04 Unsealing, M05 Greening through, M06 Increase of surface albedo, M07 Creation of open green spaces, M08 Expansion of social networks, M10 Shading, M14 Increase micro-climatic diversity) can also be shown via a drop-down menu.

There are different **perspectives** that the user can select via another drop-down menu: Avatar (user can move around the scene from a first-person perspective), Drone (or bird's eye view, it gives users a good overview of the area) and Avatar with figure (similar to the avatar perspective, here a figure is also displayed with which one moves). The avatar perspective is particularly suitable for movement in the VR environment. It offers the greatest immersion, as it comes closest to natural movement in an environment. Buildings, vegetation with their shadows as well as other landscape elements can be experienced.

Proceedings published by Eurographics - The European Association for Computer Graphics.

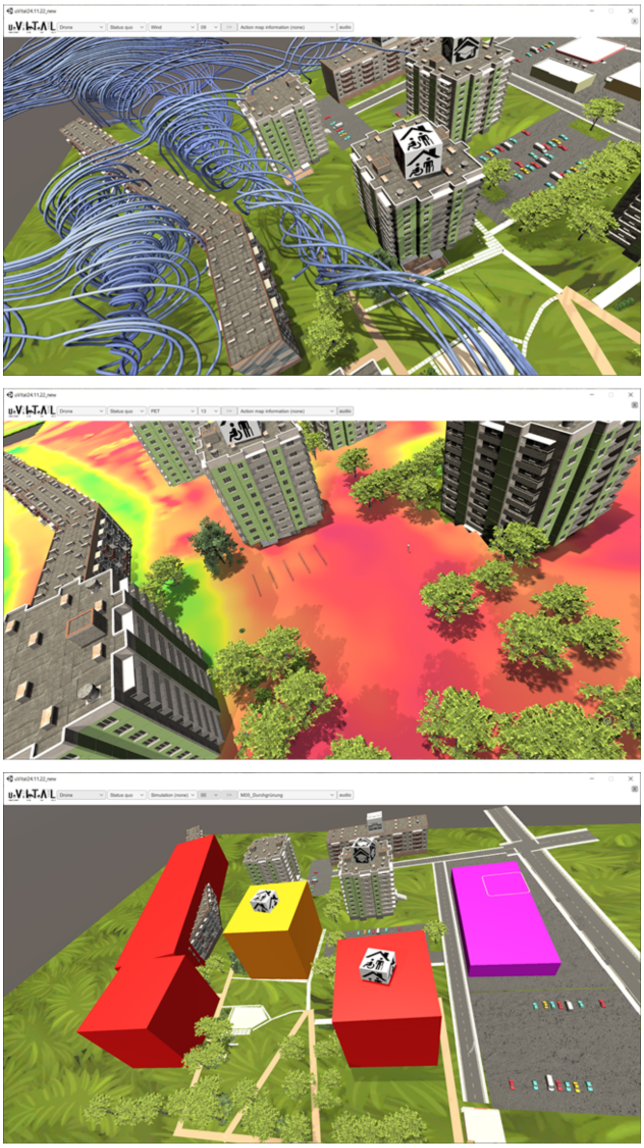

Figure 3: *Status quo scenario with streamlines of the wind simulation (top; bright blue means low wind speed, dark blue means high wind speed), a plane showing the PET values by colour (middle; reddish means high values - thermal uncomfortable, greenish means lower values - thermal comfortable), boxes around the buildings representing status of the recommended greening (bottom).*

Additional information such as statistics on socio-economic issues, results from resident surveys as well as photos of the surroundings are integrated via a 2D display. The information can be opened by clicking on the purple or blue 3D "i" in the scene.

The **sound** is controlled by selecting the scenario (status quo = traffic noise). In addition, the user has the option to mute the sound completely.

3. Results with Discussion

3.1. Scenarios

In our study, we have incorporated 3 scenarios in the application: status quo shows the current state of the area; scenario 1 and 2 are possible future scenarios in which various elements have been added to the status quo (see Fig. 5). In addition to GI, elements such as water features, facade shading, playgrounds and seating were integrated.

The results of the residents' survey (N=16), from which the priorities for concrete measures among the residents emerged, served as one basis for the development of the scenarios. For example, they were asked about desired measures to reduce heat stress in the building and the living environment. They could choose between the answer options "yes", "no", "already exists" and "don't know". The preferred measures are (answer "yes", order of decreasing agreement): Solar shading devices (78%), insulation of roof and facade (78%), tree planting (73%), fountains/water features (71%), air conditioning (63%), green facade (57%), and green roof (50%). The insulation and air conditioning measures were not taken into account in the scenarios, as these would only be visible in the interior anyway. Green facades and roofs were also not integrated, since on the one hand the statics of the buildings do not allow for green roofs and on the other hand the facades of the buildings have just recently been renovated, which makes the installation of both green roofs and facades very unrealistic. The scenarios were also based on the data from the qualitative interviews and on other best-practice projects in the area, such as the "Kolonnadengarten" (see Fig. 4).

Figure 4: *"Kolonnadengarten" as a best-practice project in the large-housing estate Leipzig-Grünau*

The scenarios created are described in more detail below:

The **status quo scenario** represents the current state of the area including the five nine-storey buildings, surrounded buildings such as a petrol station and a large block of flats, the green area including existing vegetation, an open space that used to be a playground, parking lots, paths, roads, tram tracks, seating, and clothes drying rails.

In scenarios 1 and 2, existing elements were retained (apart from the clothes drying rails) and others were added. In **scenario 1**, a water surface, seating with and without shade, a community garden, playground equipment and various types of vegetation (e.g., trees, bushes, flowers) were integrated. In **scenario 2**, the focus was, among other things, on increasing biodiversity, which is why additional vegetation types were added. In both scenarios, shading elements were integrated on the balconies of the nine-storey-buildings.

Figure 5: *Status quo scenario (top), scenario 1 (middle), and scenario 2 (bottom) from avatar view (left images) and drone view (right images)*

3.2. Transfer Events

Unity offers the possibility to build the application for different platforms. It is possible to use it on a PC, in a VR environment or with a head mounted display (HMD). As VR environment, we used the TESSIN VisLab at the UFZ, Leipzig [BFH*14].

As part of a stakeholder workshop (17.05.2022) in the "Hitzestress" project (see section 2.2), we used the VR environment to demonstrate PALM-4U results, our Planetary Health understanding and mobile measurement trajectories as a first application case for a thematic Digital Twin of the city. Primarily, the participants came from the city offices of Leipzig (health, environment, housing), university hospital Halle (epidemiology), environmental association "Ökolöwe" and had various professional backgrounds. The participants agreed that measurements and model results and their respective visualisation represents an important basis for regional recommendations for climate adaptation measures. Especially, energetic redevelopment or in general new climate related building projects should be monitored by measurements and/or visualisation/modelling before and after the construction start to be able to assess the impacts on the environment. Further, they strongly appreciate suggestions for designing GI and considering the health of the ecosystem (vitality, age, better understanding of ecosystem services through Planetary Health concepts). Concerning these discussion results, all agreed that 3D and VR are useful for communicating with the local residents and finding/monitoring suitable sites for urban heat adaptation. To sum up, they argued for the importance of an appropriate communication to cope with individual heat stress and that there is a need for climate maps to assess climate adaptation measures in public spaces. So far, VR is seen as a communication tool with the local residents or to provide information for the public on the municipal homepages. There was no discussion about the benefits for their daily work because a thematic Digital Twin and the heat stress problem alone is not sufficient for the planning practice. Thus, as an addition, further developments of the presented VR approach need to incorporate already evaluated data that can be derived from the thematic Digital Twin of the city.

Based on the first stakeholder workshop, another took place about a year later (19.04.2023) with some of the same participants, but also with a number of new ones (from the "Health for Future" initiative, the DBU and from housing companies and planning offices). This time, they could test the VR with different scenarios using a HMD. A small survey was conducted to find out whether the 3D visualisation and VR could also be used in their field of work. 44% of all participants (N=18) answered "yes" (mainly from the housing and planning industry), 28% said "no". Another 28% did not answer this question.

The VR environment was additionally used and discussed in the context of the uVITAL project meeting (09.08.2022, see Fig. 6) together with partners from the University of Huddersfield (UK) and the University of Delft who also deal with different kinds of 3D visualisations in their research (in addition to VR also BIM – Building Information Modeling). It was emphasised that the level of immersion, which varies according to the technology used, can play an important role. There was agreement that boundary objects can help to exchange knowledge and improve mutual understanding. However, it was stressed that careful consideration should be given to which tool is useful at which stage of a project or planning process.

Finally, the 3D visualisation including scenario 1 was presented to and discussed with four of the residents in the case study area and two representatives of the housing company during a meeting of the tenants' association (02.11.2022). The presentation was generally welcomed with interest by all of them. One of the challenges was not to raise expectations that cannot be met. Therefore, it has been explained repeatedly by the scientists that the main point is to show what is technically possible. One resident compared scenario 1 to a spa park and welcomed the community garden. Another said that he did not want benches and tables because they would be used by drinkers or noisy people. A representative of the housing company pointed out that the access for the fire brigade would have to be considered for the green areas close to the house. These examples from the discussion illustrate the complexity of redesigning GI from a social science perspective and underline the importance of using 3D visualisations to foster communication between different stakeholders.

We would like to point out that there is a lot of research and analysis on the usability of 3D visualisation and VR in planning. It is

Figure 6: *Colleagues from different disciplines exploring the developed scenes during the uVITAL workshop at the VisLab of the UFZ*

beyond our focus to go into more detail in this paper. We would like to draw attention to Eilola et al. 2023 who state that there is a research-practise gap that risks that research does not create applicable knowledge of the usability of 3D visualisations. They stress that there is not enough critical evaluation of 3D visualisations concerning their benefits and limitations from communicative planning theory perspective in the complex reality of planning. They suggest a common framework for developing and reporting 3D visualisations [EJK*23]. We agree with this assessment and would like to help systematise the research in this area in the future.

4. Conclusion and Outlook

In this paper, we presented a visualisation application that served as a boundary object in the communication process during the development of scenarios for urban planning and GI redesign. Based on our findings, we answer the posed research questions as follows:

To what extent can 3D visualisation / VR be used as a boundary object to create a thematic Digital Twin on the basis of which decisions can be supported? In the paper, we provide evidence that the 3D visualisation / VR can be used to analyse complex, heterogeneous data from multiple disciplines. Furthermore, it can be presented on a PC or in an immersive VR environment. This helps to bridge communication boundaries. In several transfer events, the participants stressed the importance of an intensive, group specific and linguistically appropriate communication. They confirmed the visualisation's potential to fulfil this task and to serve as a boundary object for the development of a thematic Digital Twin.

What is the potential of 3D visualisation / VR as a communication tool for GI redesign? In the context of our case study on GI redesign and with regard to urban planning, the potential of the 3D visualisation / VR presented is the integration of heterogeneous data and its processing for different stakeholder groups. However, when it comes to applying 3D visualisation / VR, it is important to bear in mind that the development of such an application is associated with a not inconsiderable amount of work, for which experts are required. Appropriate resources (finances, staff, time) and hardware infrastructure must be considered in project planning.

How can data of different characteristics be integrated and represented in 3D space? The different kinds of data were visualised according to their characteristics which allow for a systemic data integration (see section 2.1) via 3D visualisation as a boundary object. Natural objects such as buildings and vegetation were represented by a 3D object, data from simulation and climate report were assigned to abstract 3D objects. The socio-economic data available as a table were represented as graphs and projected in 2D in front of the scene, just like the photos.

How can usability be realised across different user groups? The transfer events provided unique opportunities to verify the usability of the presented visualisation pipeline among experts from very different professional backgrounds. The usability across different user groups was ensured by showing / hiding different data layers as needed. In this way, the level of detail in the scene could be customised depending on the actor and the focused question. However, it was not possible to conduct large-scale formal usability testing.

In future work, it would be beneficial to enlarge the data basis, e.g. with mobile measurements of environmental stressors [HBM*22]. These spatially and temporally highly resolved data can enhance the thematic Digital Twin and support the verification of the simulation results. Additional simulations with input data based on the scenarios would be interesting. In order to facilitate the integration of such tools into the daily work of actors, the development of workflows for their implementation would be helpful (in order to reduce the development effort) as well as further training of actors in the technologies used.

Acknowledgements

C.H. and J.P. were financially supported by the Federal Ministry of Education and Research (BMBF, funding number: 01UG2025) for the project uVITAL. J.P. and D.H. were financially supported by the German Federal Environmental Foundation (DBU) for the project *"Heat stress at neighbourhood level"* within the funding measure "Planetary Health" (grant number: 37993/01). We thank Karsten Rink from the Department of Environmental Informatics at UFZ for providing us the visualisation of the simulation data.

References

[AGL05] AHRENS J. P., GEVECI B., LAW C. C.: Paraview: An end-user tool for large-data visualization. In *The Visualization Handbook* (2005). 4

[BFH*14] BILKE L., FISCHER T., HELBIG C., KRAWCZYK C., NAGEL T., NAUMOV D., PAULICK S.: Tessin vislab - laboratory for scientific visualization. *Environmental Earth Sciences 72* (2014). doi:10.1007/s12665-014-3785-5. 6

[BT21] BURMEISTER C., TRUTE P.: Leipzig Klimaanalyse – Phase II Erweiterung der Planungshinweiskarte, 2021. URL: https://static.leipzig.de/fileadmin/mediendatenbank/leipzig-de/Stadt/02.3_Dez3_Umwelt_Ordnung_

Sport/36_Amt_fuer_Umweltschutz/Energie_und_Klima/Stadtklima/Abschlussbericht_mit_Karten_Stadtklimaanalyse_Phase_II_Leipzig.pdf. 4

[BTSW16] BILLGER M., THUVANDER L., STAHRE WÄSTBERG B.: In search of visualization challenges: The development and implementation of visualization tools for supporting dialogue in urban planning processes. *Environment and Planning B Planning and Design 44* (07 2016). doi:10.1177/0265813516657341. 2

[CJS15] CHRISTIDIS N., JONES G. S., STOTT P. A.: Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. *NATURE CLIMATE CHANGE 5*, 1 (JAN 2015), 46–50. doi:{10.1038/NCLIMATE2468}. 1

[DPD*22] DIEP L., PARIKH P., DODMAN D., ALENCAR J., SCARATI MARTINS J. R.: Problematizing infrastructural "fixes": critical perspectives on technocratic approaches to green infrastructure. *URBAN GEOGRAPHY* (2022). doi:10.1080/02723638.2022.2087947. 1

[EJK*23] EILOLA S., JAALAMA K., KANGASSALO P., NUMMI P., STAFFANS A., FAGERHOLM N.: 3d visualisations for communicative urban and landscape planning: What systematic mapping of academic literature can tell us of their potential? *Landscape and Urban Planning 234* (2023), 104716. URL: https://www.sciencedirect.com/science/article/pii/S016920462300035X, doi:https://doi.org/10.1016/j.landurbplan.2023.104716. 7

[FBS*12] FIELD C., BARROS V., STOCKER T., QIN D., AL. (Eds.): *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2012. 582 pp. 1

[FBTa21] FRENCH M. A., BARKER S. F., TARUC R. R., AL.: A planetary health model for reducing exposure to faecal contamination in urban informal settlements: Baseline findings from makassar, indonesia. *Environment International 155* (2021), 106679. doi:10.1016/j.envint.2021.106679. 1

[HAM20] HEWITT C. N., ASHWORTH K., MACKENZIE A. R.: Using green infrastructure to improve urban air quality (gi4aq). *AMBIO 49*, 1 (JAN 2020), 62–73. doi:10.1007/s13280-019-01164-3. 1

[HBM*22] HELBIG C., BECKER A. M., MASSON T., MOHAMDEEN A., SEN O., SCHLINK U.: A game engine based application for visualising and analysing environmental spatiotemporal mobile sensor data in an urban context. *Frontiers in Environmental Science 10* (2022). URL: https://www.frontiersin.org/articles/10.3389/fenvs.2022.952725, doi:10.3389/fenvs.2022.952725. 7

[HDB*17] HELBIG C., DRANSCH D., BÖTTINGER M., DEVEY C., HAAS A., HLAWITSCHKA M., KUENZER C., RINK K., SCHÄFER-NETH C., SCHEUERMANN G., KWASNITSCHKA T., UNGER A.: Challenges and strategies for the visual exploration of complex environmental data. *International Journal of Digital Earth 10*, 10 (2017), 1070–1076. doi:10.1080/17538947.2017.1327618. 2

[HPHS] HELBIG C., POESSNECK J., HERTEL D., SEN O.: uvital. URL: https://zenodo.org/record/7885795. 3

[HS19] HERTEL D., SCHLINK U.: Decomposition of urban temperatures for targeted climate change adaptation. *Environmental Modelling & Software 113* (2019), 20–28. doi:10.1016/j.envsoft.2018.11.015. 1

[HZS22] HERTEL D., ZEIDLER J., SCHLINK U.: Urban climate modeling. In *Final Report Phase 1 - Ergebnisbericht der ersten Phase unserer Klima-Initiative*. Helmholtz-Centre for Environmental Research - UFZ, Leipzig, 2022, pp. 128 – 131. 3

[Hö99] HÖPPE P.: The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment. *International Jornal of Biometeorology 43*, 2 (1999), 71–75. doi:10.1007/s004840050118. 4

[KP21] KABISCH S., PÖSSNECK J.: *Grünau 2020: Ergebnisse der Bewohnerbefragung im Rahmen der Intervallstudie "Wohnen und Leben in Leipzig-Grünau"*. Tech. Rep. 1/2021, Helmholtz-Centre for Environmental Research - UFZ, Leipzig, Germany, 2021. URL: https://www.ufz.de/index.php?de=20939&pub_id=24705, doi:10.57699/76TC-4757. 2

[Lin17] LINDHOLM G.: The implementation of green infrastructure: Relating a general concept to context and site. *SUSTAINABILITY 9*, 4 (APR 2017). doi:10.3390/su9040610. 1

[MA14] MADUREIRA H., ANDRESEN T.: Planning for multifunctional urban green infrastructures: Promises and challenges. *URBAN DESIGN INTERNATIONAL 19*, 1 (SPR 2014), 38–49. doi:10.1057/udi.2013.11. 1

[MCM*17] MORABITO M., CRISCI A., MESSERI A., MESSERI G., BETTI G., ORLANDINI S., RASCHI A., MARACCHI G.: Increasing Heatwave Hazards in the Southeastern European Union Capitals. *Atmosphere 8*, 7 (2017). URL: http://www.mdpi.com/2073-4433/8/7/115, doi:{10.3390/atmos8070115}. 1

[MLB*21] MOKAS I., LIZIN S., BRIJS T., WITTERS N., MALINA R.: Can immersive virtual reality increase respondents' certainty in discrete choice experiments? a comparison with traditional presentation formats. *Journal of Environmental Economics and Management 109* (2021), 102509. URL: https://www.sciencedirect.com/science/article/pii/S0095069621000784, doi:10.1016/j.jeem.2021.102509. 2

[NKB*22] NAZARIAN N., KRAYENHOFF E. S., BECHTEL B., HONDULA D. M., AL.: Integrated assessment of urban overheating impacts on human life. *Earth's Future 10*, 8 (2022), e2022EF002682. doi:10.1029/2022EF002682. 1

[NS00] NORTH C., SHNEIDERMAN B.: Snap-together visualization: a user interface for coordinating visualizations via relational schemata. In *Proceedings of the working conference on Advanced visual interfaces - AVI '00* (New York, New York, USA, 2000), ACM Press, pp. 128–135. doi:10.1145/345513.345282. 4

[NvE*21] NAZEMI M., VAN EGGERMOND M., ERATH A., SCHAFFNER D., JOOS M., AXHAUSEN K. W.: Studying bicyclists' perceived level of safety using a bicycle simulator combined with immersive virtual reality. *Accident Analysis & Prevention 151* (2021), 105943. URL: https://www.sciencedirect.com/science/article/pii/S0001457520317632, doi:10.1016/j.aap.2020.105943. 2

[Pei21] PEI L.: Green urban garden landscape design and user experience based on virtual reality technology and embedded network. *Environmental Technology & Innovation 24* (2021), 101738. URL: https://www.sciencedirect.com/science/article/pii/S2352186421003862, doi:10.1016/j.eti.2021.101738. 2

[RFB*21] RODRIGUEZ M., FU G., BUTLER D., YUAN Z., SHARMA K.: Exploring the spatial impact of green infrastructure on urban drainage resilience. *WATER 13*, 13 (JUL 2021). doi:10.3390/w13131789. 1

[RSL*20] RAGHAVAN S., SIMON B. Y. L., LEE Y. L., TAN W. L., KEE K. K.: Data integration for smart cities: Opportunities and challenges. In *Computational Science and Technology* (Singapore, 2020), Alfred R., Lim Y., Haviluddin H., On C. K., (Eds.), Springer Singapore, pp. 393–403. 1

[SG89] STAR S., GRIESEMER J.: Institutional ecology, translations and boundary objects - amateurs and professionals in berkeleys-museum-of-vertebrate-zoology, 1907-39. *Social Studies of Science 19*, 3 (August 1989), 387–420. doi:10.1177/030631289019003001. 2

[Wil20] WILLIS P.: Headset go - how can virtual reality tools help meteorological research? industry experts discuss the tech's benefits. *Meteorological Technology International* (September 2020), 18 – 22. URL: https://www.ukimediaevents.com/publication/b853e52b. 2

[WZS22] WOLLSCHLÄGER N., ZINCK F., SCHLINK U.: Sustainable urban development for heat adaptation of small and medium sized communities. *Land 11*, 9 (2022). 1

[ZZ21] ZHANG R.-X., ZHANG L.-M.: Panoramic visual perception and identification of architectural cityscape elements in a virtual-reality environment. *Future Generation Computer Systems 118* (2021), 107–117. URL: https://www.sciencedirect.com/science/article/pii/S0167739X20330843, doi:10.1016/j.future.2020.12.022. 2