The Digital Twin

Tackling Urban Challenges with Models, Spatial Analysis and Numerical Simulations in Immersive Virtual Environments.

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For the built environment's transformation we are confronted with complex dynamics connected to economic, ecologic and demographic change (Czerkauer-Yamu et al., 2013; Yamu, 2014). In general, cities are complex systems being a ``heterogeneous mosaic'' of a variety of cultures and functions, characterised by diverging perceptions and interests (ibid). The juxtaposed perceptions and interests in relation to ongoing spatial processes of change create a particularly complex situation. Thus, for planning processes we are in need of approaches that are able to cope not only with the urban complexity but also allow for participatory processes to empower citizens. This paper presents the approach of using Digital Twins in virtual reality (VR) for civic engagement in urban planning, enriched with quantitative and qualitative empirical data as one promising approach to tackle not only the complexity of cities but also involve citizens in the planning process.

Keywords: *Digital Twin, Collaborative Planning, Planning and Decision Support, Participation, Virtual Reality, Global System Science*

INTRODUCTION

This approach enables citizens in a novel way through the use of digital emerging technologies. Until now, Digital Twins have been mainly used in the field of engineering and their implementation for towns have only recently been discussed (Batty, 2018). Digital Twins are digital representations of material or immaterial objects, such as machines, from the real world. They enable comprehensive data exchange and can contain models, simulations and algorithms describing their physical counterpart and its features and behaviour in the real world (Kuhn, 2017). To enhance a real life perception, Digital Twins can be implemented in Virtual Realities (VR). A Digital Twin is not an exact copy. This results from a classical dilemma in modelling, as models always have a certain level of abstraction and only represent physical reality with an error margin. A Digital Twin can be best characterised as a container for models, data, and simulation. The term "Digital Twin" has been coined and first used in relation to mechanical engineering, where they have already been applied for several years (Kuhn, 2017; Dembski et al., 2019).A criticism of Digital Twins is that they represent only a limited set of variables and processes and rarely include any of the processes that determine how a city works in terms of its social and economic functions (Batty, 2018). We therefore conclude the paper with a discussion of the presented results and further research direction how to include more social and economic functions using a synthetic population model (Dembski et al., 2019). Using a Digital Twin in VR not only is a novel way for collaborative planning processes, but also enables participants with different backgrounds to achieve an agreement. Digital Twins for towns will inform urban planners and designers in understanding impacts of intended urban change, also allowing citizens to have a voice and opportunity to influence public decisions for smart, sustainable cities already at an early stage (Dembski et al., 2019). The implementation of different analytical methods, as well as data and simulations for traffic and emissions, among others, is a great improvement for using the Digital Twin as an analytic and predictive tool.In general, digital technologies and their applications are of great importance for processes bridging formal and rational knowledge with informal and implicit knowledge. Our approach aims to support the creation of knowledge for smarter, more sustainable governance of urban regions involving the experience of citizens (civic science) supporting a democratic planning process. Consequently, this paper contributes to the debate of digital tools and their development with mixed methods for civic engagement and decision support in the field of urban planning. Our research involves 3D interactive simulations in virtual reality in combination with qualitative and quantitative data and methods such as space syntax. We present the development and test application of a Digital Twin in virtual reality for the 30,000-person town of Herrenberg, Germany. Our modelling approach includes a mixed method of 3D models, simulations, 3D mapping, and a street network model with space syntax. For citizen participation, the Digital Twin was embedded in the collaborative visualisation and simulation environment "COVISE." The Digital Twin for Herrenberg was exposed to approximately 1,000 citizens using both a mobile and stationary virtual reality environment (Dembski et al., 2019). For verification and consolidation, a survey was carried out. The results demonstrated that the use of this method and technology could significantly aid in participatory and collaborative processes (Ruddat, 2019).

In general, visualisation of complex processes and data related to participation of heterogeneous groups is essential. To that end, we developed a Digital Twin that can be applied and visualised seamlessly across all scales, on multiple layers, and in different categories of data in virtual and augmented realities for collaborative and participatory processes (PP), focusing on planning and decision support. For all participatory processes, we used collaborative VR environments. The advantage of using VR environments-such as stereoscopic back projection units, large 3D displays respectively tiled display systems or CAVEs (Cave Automatic Virtual Environment) -is that different participants with diverging professional and personal backgrounds can be informed simultaneously. These technologies can enhance discussion and help build consensus among stakeholders (Dembski et al., 2019). In this context, VR facilities, Digital Twins and visualisation techniques are highly useful: As Arnstein (1969) points out, it needs real power and not empty rituals to affect the outcome of such processes. Our approach described here allows not only citizens, but also decision makers and planning professionals to use the tools to achieve partnership: A Digital Twin offers great potential in the field of digital tools. Enriched with quantitative and qualitative empirical data, Digital Twins serve as one promising approach for tackling not only the complexity of cities, but also to involve citizens in the planning process (Dembski et al., 2019).

Beyond these applications, it has great potential to support option testing and scenario development for different planning fields and at all scales. Using a Digital Twin in VR is not only a novel way for collaborative planning processes, but also facilitates consensus building among participants with different backgrounds (Dembski et al., 2019). This is further connected to a common learning process linked to educational aspects such as involving youth or different other groups of citizens who are usually less involved in such processes. As Glaeser et al. (2006) rightly points out, better-educated citizens are more likely both to preserve and strengthen democracy.

PILOT APPLICATION OF THE DIGITAL TWIN: HERRENBERG, GERMANY

Herrenberg is a medieval town in south-western Germany with a population of approximately 30,000. The town encountered urban growth in particular during the industrialisation age and after World War II. The city belongs to the metropolitan region of Stuttgart with 5.2m inhabitants - a region characterised by fragmented peri-urban landscapes - a diffuse belt in-between urban agglomeration and rural landscapes characterised by multiple agglomerations, low population density (Dembski et al., 2019). This results in high dependency on infrastructure and increasing individual transport. Stuttgart's hinterland can be characterised in general by high levels of traffic, mainly reasoned in the high dependency on transport for commuting, fragmented communities and a lack of spatial governance (Ravetz et al., 2013).

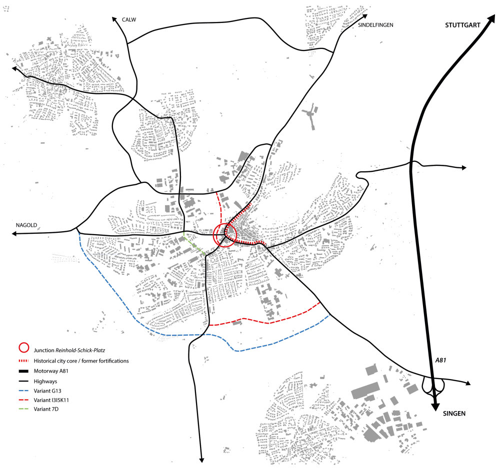

Figure 1
Figure-ground diagram of Herrenberg illustrating the high ranked street network and three traffic-planning scenarios. (Dembski, 2019)

Herrenberg consists of a homogeneous historic core; a fragmented urban fabric defines the urban fringe. The historic centre is highly affected by individual motorised traffic due to planning decisions and implementations in the past: A main road is leading the traffic directly through the historic core where it is merged with three highways. Thus, this area is exposed not only to high traffic volumes but also to environmental pollution by emissions and noise. In order to solve this urban challenge, the city of Herrenberg developed an integrated mobility plan (IMEP 2030), which shall serve as the guideline for the mobility development over the next 15 years. This process was supported by civic engagement. During the longstanding planning phase, nine different traffic scenarios have been developed until in May 2019 the implementation of one of the variants has been decided. We used IMEP 2030 and other urban planning projects as a test application for our Digital Twin to approach a novel way for enhancing collaborative planning processes.

METHODS AND DATA

Our research method is empirical and computational using a mixed method approach. In this research, we developed a Digital Twin and visualised it in VR for supporting participative and collaborative planning processes. The Digital Twin is set up as follows: (i) a morphological model (built environment); (ii) a street network model using the theory and method of space syntax; (iii) an urban mobility simulation with SUMO and wind flow simulation with ; (iv) qualitative and quantitative data using Volunteered Geographic Information (VGI) with a mobile application "Reallabor Tracker" developed for this purpose; and (v) a pollution simulation using an empirical data set from a sensor network (Dembski et al., 2019). For the Digital Twin, we used the collaborative visualisation and simulation environment 'COVISE', an extensible distributed software environment to integrate simulations, post processing and visualisation functionalities in a seamless manner. COVISE is designed for collaborative working, allowing users to collaborate through CSCW during the analysis of the Digital Twin or other data and models. COVISE supports projection based virtual environments such as CAVEs (Cave Automatic Virtual Environment), Powerwalls, tiled displays and domes but also a wide variety of HMDs (Head-Mounted Displays). Users can analyse their datasets intuitively in a fully immersive environment through state-of-the-art visualisation techniques such as direct volume rendering, high performance point cloud rendering and traditional surface rendering or ray casting (ibid). For the town of Herrenberg, Germany, we carried out a pilot-application.

The Digital Twin builds on a solid 3D city model based on a digital building model (i) provided by regional authorities (LGL), where additional detailed modelling was supplemented and 3D scans were integrated. While the model includes an overall level of abstraction, selected potential architectural projects with an expected impact on the neighbourhood and citywide level were represented in detail. The model was developed with a focus on the support of decision makers as well as for the use in participatory processes.

By using space syntax (ii) and the software depthmapX, we could analyse the potential through movement which refers to the movement passing the shortest routes from all points to all points in the road network (cf. Hillier, Burdett, Peponis, Penn, 1987).We analysed the status quo (2018) as well as nine different traffic-planning options, developed by traffic planners for reducing congestion in the city's core (Brenner, 2014). The results show different expected traffic development and build the basis for further application of methods.For the space syntax model, a hybrid model was chosen that combines road centre lines based on geographic information data and axial lines for areas with greater detail. Notably, emission data linked to airflow simulation were coupled with the NACH (angular segment analysis) mean value for neighbouring street segments in the length of 60m to 100m (Dembski et al., 2019). In the following step, the model was converted from two-dimensional to three-dimensional data for the visualisation in VR. In order to achieve three-dimensional space syntax visualisation, we developed new modules for COVISE and the OpenCOVER software. These novel features allow for an automated processing of two-dimensional geo-referenced space syntax data to be presented in three-dimensional virtual reality for collaborative platforms like the Cave Automatic Virtual Environment (CAVE) or other devices like 3D-Powerwalls or head mounted displays.

For a better understanding of traffic behaviour, we extended the model with a traffic simulation using the software SUMO (Kraizewicz, 2010) . This simulation uses a microscopic, space continuous and time discrete car-following model and lane-changing model. The results of the simulation are displayed in 3D as individual cars, trucks and buses driving through the 3D city model. A new plugin was developed to simulate and visualise changes in modal-split and amount of travel in real-time. This allows illustrating different scenarios and visions with the focus on traffic reduction.

Data, such as particulate matter, temperature, and humidity from the sensor network, was correlated with the space syntax model respectively its calculated values for route segments (potential through movement) and combined with traffic simulation and traffic counts (the latter provided by traffic engineers). For the integrated airflow simulation, official weather and climate data were integrated (prevailing wind direction and average wind velocity). This combination allows investigators to relate emissions to the potential volume of traffic and the distribution of emissions taking the wind and factors like temperature and humidity into account. This is also transferable to other emissions (simulation of NOx, CO2, etc.) and climate data (simulation of floods, urban heat, air lanes, for example) and is of course scalable to other sizes of cities and regions. The processing of required (big) data and the simulations can be calculated in real time supported by high-performance computing (HPC) (Dembski et al., 2019).

Volunteered geographic information (iv) can be accessed in different ways (Poplin, 2012). With

Figure 2
Space syntax NACH analysis of three traffic planning scenarios and the current situation in 2D. (Dembski, 2018)

the development of mobile devices such as smart phones and tablet computers, possibilities opened up novel ways of collecting geographic data: Information can be collected on site, directly where it was observed by the users, in this case, citizens (iv). Goodchild writes about citizens acting as sensors (Goodchild 2007) contributing data to GIS-based systems that are often free of charge, open source, and available as mobile applications for smartphones or other mobile technologies. He coined the term "Volunteered Geographic Information (VGI)." In a VGI environment, the user contributes his or her knowledge about the environment and is able, through user-friendly interfaces, to enter this data into the system, which stores it in a geographic database. VGI is compatible with GIS and can relate this geo-referenced data with other attributes, such as the characteristics of information, objects, or temporal and spatial information. The smartphone as hardware supports geo-referenced, photographic, and audio data, as well as comments written as text right on site. This data was implemented and visualised in the Digital Twin via a COVISE interface and tool in near real time. In order to collect empirical data through VGI, the mobile application "Reallabor Tracker" was developed (Dembski et al., 2019). The application allows users rate the quality of stay and readability of the cityscape based on urban elements in the thinking line of Lynch (1960) and registers their stationary activities and choice of transport. Furthermore, the ap-

Figure 3
Stereoscopic visualisation of the Digital Twin in the CAVE: a) Current situation / point clouds in scale 1:1, walking mode; b) space syntax NACH analysis linked to data of particulate matter and airflow analysis in big scale and flyby-mode; c) Overlay of space syntax analysis and movement patterns (VGI); d) Movement patterns combined with other VGI data collected with the mobile application. (Dembski, 2019)

plication registered spatially and chronologically differentiable movement patterns using traces created by GPS data. Open spaces were rated according to evoked emotions such as trouble spots or the spatial quality of paths or for stationary activities as well as urban barriers, etc. (Figure 4). Users had the possibility to take geo-referenced pictures, voice and/or urban soundscape recording and text notes from specific locations and situations. The empirical VGI data created by users of the mobile application ("Reallabor Tracker") were linked with the space syntax model and visualised for interactive use in virtual realities (Gudat, 2019).

Figure 4
Volunteered geographic information (movement traces, stationary activity, quality of public spaces) collected by young citizens using a mobile application: Georeferenced data in the Digital Twin, visualised in the CAVE (VR). (Dembski, 2019)

Because of well-known serious far-reaching effects on health, the air quality is monitored in most middle European cities. This usually occurs by networks of individual air quality measuring stations operated by state authorities. Because of high costs of hardware and maintenance, they offer only very low resolution for spatial measures (Dembski et al., 2019). The fact that emissions are not stationary but mobile, and that they are subject to a high level of spatial and temporal variability, there are questions about the capability of official sensor networks to gather adequate data of defined neighbourhoods and areas (Kraft, 2018). Alternatively, air quality can be determined via crowdsourcing. This term is used in earth sciences for the collection of environmental data by a potentially high number of people. Volunteers create geographic information (VGI) that usually is provided by states agencies or other official institutions (Goodchild, 2007).

Several civic engagement projects with the aim to collect emission data by using low-budget sensors already have emerged (Ling-Jyh et al., 2017). These projects usually rely on Wi-Fi or less common LoRaWAN (Long Range Wide Area Network) for data transmission. The sensors are collecting in most cases data on particulate matter, air temperature and humidity and are quite reliable. Occasional incorrect measurement of single stations is balanced with measurements of the other stations. Data is collected and stored on a server for almost real-time availability to be used in analysis, simulations and visualisations. We collected empirical data using a sensor network for temperature, humidity and particulate matter. This data was then correlated with a traffic simulation (Dembski et al., 2019).

COLLABORATIVE VISUALIZATION AND SIMULATION ENVIRONMENT

COVISE is an open-source modular visualisation system, designed to support collaborative visualisation of data in virtual environments as well as on the desktop. The architecture of COVISE allows developers to extend the existing functionality by integrating new code as modules. In a visual application builder, these modules are connected to form a dataflow network (Figure 5).

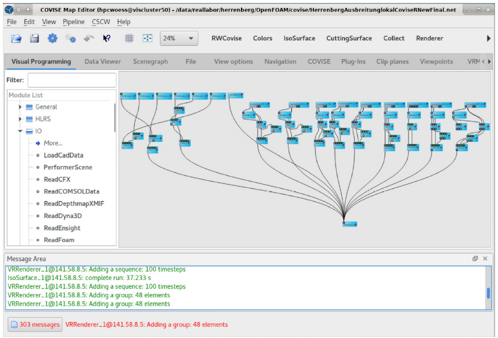

Figure 5
The COVISE desktop user interface: Visualisation pipeline of the “Herrenberg” dataset. (Wössner, 2019)

At the end of the pipeline there is a render module, which can either be a desktop renderer, or the VR- oriented render module, OpenCOVER. The pollution simulation was carried out in OpenFOAM. COVISE already provides a read module to read in results from parallel unsteady OpenFOAM simulations and existing modules can be used to visualise geometry, cutting surfaces, isosurfaces, streamlines, etc. New modules have been introduced to read depthmapXnet data, project georeferenced data and drape 2D data to 3D elevation maps. All this data is then rendered in OpenCOVER together with the 3D city model. OpenCOVER is based on OpenSceneGraph and supports any type of projection- based VR environment such as CAVEs, powerwalls, domes, or tiled displays. It further supports VR and AR Head Mounted Displays. C++ plugins can be developed to extend the functionality of OpenCOVER. A number of plugins have been developed or extended to visualise the data for this research. Large-scale terrains are rendered through Virtual Planet Builder (VPB) or osgEarth. VPB had to be extended to align the uneven terrain to high-resolution streets represented in the OpenDRIVE format in order to prevent visual artefacts. Point clouds from terrestrial LIDAR scans (light detection and ranging) have been sorted into an octree data structure for efficient rendering. 3D city models can be loaded in various data formats: CityGML and DXF in case of the pilot-application Herrenberg.

OpenCOVER not only provides 3D navigation in the virtual model but also allows for interaction with the visualisation modules thus cutting surfaces and streamlines can be interactively placed anywhere within the city to analyse the airflow. Colour maps or the size of tubes representing space syntax, for example, results can be visually and graphically adjusted to one’s liking.

COLLABORATIVE PLANNING AND PUBLIC PARTICIPATION

The use of a Digital Twin based on VGI and crowdsourcing for civic science fits well into Arnstein’s ladder of citizens’ participation: It enhances low-threshold access to information, participation in data acquisition and ensures a broad understanding of complex topics related to urban planning. Arnstein (1969) points out, that power is in fact redistributed through negotiation between citizens and powerholders (rung 6 of the ladder). A tool like the Digital Twin enables citizens to engage in trade-offs as strong partners (Dembski et al. 2019).

For the participatory process we used stationary (Figure 7) as well as mobile virtual reality environments (Figure 6). The mobile version consists of a powerful computer, a mobile back-projection wall, a 3D projector including optical tracking equipment and a Vive Pro Head Mounted Display. The stationary virtual environment we used was a five-sided CAVE

(Cave Automatic Virtual Environment) at the High-Performance Computing Center Stuttgart. Participants could experience the interactive model in collaborative VR environments in groups of 10, in a time frame from 10 to 15 minutes. For both, the mobile and the stationary VR environment active stereo shutter glasses and an optical tracking system for navigation were used for interaction and correct representation of the perspective for the viewers. More than 700 people of different age and backgrounds in particular children and adolescents took part in multiple participatory processes "on site." Furthermore, with the help of VR, we could involve citizens with migration and different language background, groups of elderly people and even deaf and otherwise challenged participants. All of these are marginalised groups that are commonly not included into urban planning citizen participation (Dembski et al., 2019).

Figure 6
A mobile immersive VR during a participatory process with participants of various age with different backgrounds in Herrenberg (on-site). (Dembski, 2019)

In addition, we offered participatory workshops in the CAVE, by its nature a stationary virtual reality environment situated at HLRS. This was the option mainly used for planning professionals, decision makers and youth organisations. In total, approximately 300 participated using the stationary VR environment and approximately 700 participants using the mobile VR (ibid).

A questionnaire was developed with the support of a sociologist and we gathered 40 responses with an age range of 16-80. The respondents had diverse professional and educational backgrounds, from students, educators and police officers to IT experts and decision makers.

The questionnaire consisted of 9 questions focussing on quantitative queries about the perception of the visualisation in form of a polarity profile as well as open questions relating to the perceived use and potentially missing information. This enabled us to collect both quantitative and qualitative data. Based on this survey, we wanted to find out about the users' acceptance regarding the Digital Twin and virtual reality versus conventional instruments used for participatory processes (Dembski et al., 2019).

The results showed that all in all, the experience in the VR environment was received very positively: The Digital Twin, specifically its representation in VR, was perceived as very beneficial and interesting. Visual evidence was also very well regarded. For the participants it was equally understandable, clear and entertaining. Users were also asked about the benefits of virtual urban models in the context of public participation processes respectively municipal planning processes. In both cases the answer was clear: Almost all participants agreed on the usefulness of such tools. "The situation can be experienced from all perspectives," "It provides a better understanding concerning consequences and implications," "Easily understandable - everybody can understand planning better that way," were just some of the comments given by the participants (Ruddat, 2019; Dembski et al., 2019).

Clarity and transparency are seen as major advantages. These user expectations are important when it comes to interaction between administrations, different experts and citizens and, in this context, for communicating urban planning and design topics simply and comprehensibly. A Digital Twin as built up in our case study is certainly suitable to convey complex information from administration and planning professionals to citizens and, vice versa, to include citizens in urban planning and design processes in the sense of civic engagement and citizen science (Dembski et al., 2019).

Figure 7
A group of young citizens using the CAVE during a participatory process at the High-Performance Computing Center Stuttgart. (Dembski, 2018)

CONCLUSIONS

In this paper we set out to present the development of a Digital Twin involving different models, methods, analysis and simulation. It summarises our development of a Digital Twin, a novel tool in the field of urban planning. We used a variety of techniques and methods such as 3D modelling, urban mobility simulation, wind flow simulation, space syntax, people's movement patterns, stationary activity data and qualitative data to configure the Digital Twin. For our pilot application we chose the 30,000-person town of Herrenberg, Germany-an urban area in the peri-urban region of Stuttgart that contains high traffic volume and pollution. This gave us the opportunity to test a series of scenarios and potential solutions as well as evaluate their impacts using a real-life case. It serves as our first European application for a Digital Twin for urban planning and design. The Digital Twin allowed us to gain a better understanding of potential solutions for urban challenges involving public decision-making to reach consensus.

For consolidation and validation of the Digital Twin we carried out a questionnaire with 40 participants which will enable us to not only evaluate the meaningfulness of our approach, but also to adjust the Digital Twin to the needs of citizens in order to provide with an easily understandable model for the complexity of the built environment.

By its nature of a model and therefore an abstraction of reality, a Digital Twin does not include all real-life information. It is an objective to achieve similarities to the real world and a level of detail accurate enough for concrete (but complex) problems. Furthermore, Batty (2018) states that there remains a strong need for additional social, economic and environmental data.

Consequently, we are continuing our research in the context of Global System Science (GSS) related to these areas. Therefore, we are currently working on an integrative toolbox for global systems analysis. The integration will be centred on recent methodological advances in the construction and use of synthetic populations. These synthetic populations provide models of given populations, typically of humans, but also of cars, buildings and more. A synthetic population is based on individuals that are different from the actual ones, but in such a way that the population as a whole matches the empirical one in the distribution of attributes and relations that matter for the problem at hand. In our current research, we aim to provide generators for such populations at a global (worldwide) scale while also at smaller scales. The case study of the Digital Twin described here forms just one piece in the big puzzle (Dembski et al., 2019).

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