Digital Twin, Virtual Reality and Space Syntax

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316

DIGITAL TWIN, VIRTUAL REALITY AND SPACE SYNTAX:

CIVIC ENGAGEMENT AND DECISION SUPPORT FOR SMART, SUSTAINABLE CITIES.

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ABSTRACT

This paper presents the development of a Digital Twin in Virtual Reality (VR) for civic engagement in urban planning. Herein used approach enables to empower citizens in a novel way using digital, emerging technologies. Until now Digital Twins have been mainly used in the field of engineering and their implementation for towns only have been recently discussed (Batty, 2018).

A Digital Twin is a digital representation enabling comprehensive data exchange and can contain models, simulations and algorithms describing their counterpart and its features and behaviour in the real world (Kuhn, 2017). We present the development and test application of a Digital Twin in Virtual Reality for the 30,000 people town of Herrenberg in Germany. Our modelling approach includes a mixed method with 3D models, simulations, 3D mapping and computational analysis with space syntax as a socio-spatial approach. For citizen participation the Digital Twin was embedded in the collaborative visualization and simulation environment “COVISE”. The Digital Twin for Herrenberg was exposed to approximately 1,000 citizens using a mobile and stationary Virtual Reality environment. For verification and consolidation, a survey was carried out. The results demonstrated that the use of this method and technology could be very supportive in participatory and collaborative processes.

A criticism of Digital Twins is that they abstract only a limited set of variables and processes and rarely includes any of the processes that determine how the 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.

Digital twins for towns will help urban planners and designers to understand and inform about impacts of intended urban change with citizens having a voice and the opportunity to influence public decisions for smart, sustainable cities. This democratic decision-making process empowers people to reach public consensus.

KEYWORDS

Digital twin, virtual reality, volunteered geographic information, space syntax, civic engagement

1. INTRODUCTION

In this paper we present a novel development using a mixed method approach, namely a digital twin for urban planning in Virtual Reality (VR) integrating space syntax using a collaborative visualization environment. The aim of this paper is to contribute to the debate of citizen participation and civic engagement with emerging digital tools.

In general, visualization of complex processes and data for the participation of heterogeneous groups is essential. Thus, we developed a Digital Twin, which can be applied and visualized seamless 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 Virtual Reality environments. The advantage of using such VR environments like e.g. 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. Discussions can be enhanced and joint consensus for solutions approached.

VR facilities, Digital Twins and visualization techniques are highly useful when it comes to participation. As Arnstein (1969) points out, it needs real power and not empty rituals to affect the outcome of such processes. Our approach could give citizens but also decision makers and planning professionals the tools to achieve partnership.

1.1 DIGITAL TWIN

Digital Twins offer a great potential in the field of digital tools 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. Digital Twins are digital representations of material or immaterial objects like e.g. machines from the real world. They enable comprehensive data exchange and can contain models, simulations and algorithms describing their counterpart and its features and behaviour in the real world (Kuhn, 2017). A Digital Twin is not an exact copy. This is resulted in a classical dilemma on the topic of modelling as models always have a certain level of abstraction. A Digital Twin can be best characterized as a container for models, data and simulation. The term “Digital Twin” has been coined and used first in relation to mechanical engineering where they are mainly applied for several years.

Only recently implementations for towns are discussed (Batty, 2018). To enhance a real life perception, Digital Twins can be implemented in Virtual Realities (VR). This immersivity enables citizens to better understand the Digital Twin and enables them to participate. In general, 3D models and visualizations are used to overcome lack of communication and therefore supports decision-making. Using a Digital Twin in VR not only is a novel way for collaborative planning processes, but also enables to achieve consensus among participants with different backgrounds. This is furthermore connected to a common learning process linked to educational aspects. As Glaeser et al. (2006) rightly points out, better-educated citizens are more likely both to preserve and strengthen democracy.

1.2 REAL-LIFE AND EMPIRICAL DATA FOR THE DIGITAL TWIN

1.2.1 VOLUNTEERED GEOGRAPHIC INFORMATION (VGI) AND CIVIC SCIENCE

With the development of mobile devices such as smart phones and tablets new possibilities opened up to novel ways of collecting geographic data: Information can be collected on site, directly where observed by the user resp. citizen. Goodchild writes about the citizens acting as sensors (Goodchild 2007a, Goodchild 2007b, Goodchild 2007c) contributing data to GIS-based systems that are often free of charge, open source and available as mobile applications for e.g. smartphones. He created 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 like e.g. the characteristics of information, objects or temporal and spatial information. The smartphone as hardware supports e.g. geo-referenced photographic, audio data and comments written as text right on site. These data were implemented and visualized in the digital twin via a COVISE interface and tool in almost real time or delayed.

1.2.2 SENSOR NETWORKS

Because of serious far-reaching effects on health, the air quality is monitored in most of middle European cities. This usually occurs by a net of individual air quality measuring stations operated by states authorities. Because of high costs concerning hardware and maintenance, they offer only very low resolution for spatial measures. The fact that emissions are not stationary but mobile and that they are subject to a high level of spatial and temporal variability, questions 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. The 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).

Some civic engagement projects with the aim to collect emission data by using low-budget sensors already have emerged (Ling-Jyh et al., 2017). Usually these projects rely on Wi-Fi or LoRaWAN (Long Range Wide Area Network) for data transmission. These sensors usually are collecting data on particulate matter, air temperature and humidity and are quite reliable. Incorrect measurement of single stations can occur but are balanced with measurements of the other stations. Data are collected and stored on a server for an almost in real-time availability to be used in simulations, analysis and visualizations.

2. DATASETS AND METHODS

Our research methodology is empirical and computational using a mixed method approach. In this research we developed a Digital Twin and visualised it in Virtual Reality for collaborative planning. 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[1]; (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. For the Digital Twin the collaborative visualization and simulation environment 'COVISE' was used. It is an extendable distributed software environment to integrate simulations, post processing and visualization functionalities in a seamless manner. COVISE is designed for collaborative working allowing distant collaboration during the analysis of the Digital Twin. COVISE supports virtual environments such as CAVEs (Cave Automatic Virtual Environment) and HMDs (Head Mounted Displays). The user can thus analyse their datasets intuitively in a fully immersive environment through state of the art visualization techniques. A pilot-application was carried out for the town of Herrenberg in Germany.

For the morphological model, a solid 3D city model based on a digital building model provided by regional authorities and additional detailed modelling supplemented with 3D scans forms the twin's basis. While the model entails an overall level of abstraction, selected potential architectural projects with an expected impact on the neighbourhood were represented in detail. A mathematical street network model was implemented and angular segment analysis (NACH) for understanding potential through movement was conducted. For the space syntax model a hybrid model was chosen combining road centre lines based on geographic information data and axial lines for areas with greater detail. In a next step, the model was converted from two-dimensional data to three-dimensional, geo-referenced data for the visualization in VR. In order to achieve three-dimensional space syntax visualization, we developed new modules for COVISE and OpenCOVER software. This novelty allows for an automated processing of two-dimensional space syntax data in this form in order to be presented in three-dimensional virtual reality for collaborative platforms like the Cave Automatic Virtual Environment (CAVE). In addition, for a better understanding of traffic behaviour we extended the model with a traffic simulation using the software SUMO. This simulation uses a microscopic, space continuous and time discrete car-following model and lane-changing model (Kraizewicz, 2010). The results of the simulation are displayed in 3D as individual cars, trucks and buses driving through the 3D city model. The digital twin also includes qualitative and quantitative data using Volunteered Geographic Information (VGI) and sensor network data. In order to collect empirical data through VGI, the mobile application "Reallabor Tracker" was developed through which users rated the quality of stay and readability of the cityscape based on urban elements in the thinking line of Lynch (1960) and registered their stationary activities and modal split. Furthermore, the application registered movement patterns using traces (GPS). Open spaces were rated according to evoked emotions like e.g. trouble spots or the spatial quality for stationary activities as well as urban barriers etc. Users indicated their mode of transport and 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 visualized for interactive use. In addition, data such as particulate

[1] https://www.dlr.de/ts/en/desktopdefault.aspx/tabid-9883/16931_read-41000/

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 respectively climate data were integrated (prevailing wind direction and average wind velocity). This combination allows relating 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 NO_x, CO_2, etc.) and climate data (e.g. simulation of floods, urban heat, air lanes) and 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).

2. 1. TEST APPLICATION: THE TOWN OF HERRENBERG, GERMANY

Herrenberg is a medieval town in the South of Germany with a population of approximately 30,000. The town encountered urban growth in particular during the industrialization age and after WWII. The city belongs to the metropolitan region of Stuttgart with 5.2m inhabitants – a region characterized by fragmented peri-urban landscapes – a diffuse belt in-between urban agglomeration and rural landscapes characterized by multiple agglomerations, low population density. This results in high dependency on infrastructure and increasing individual transport. Stuttgart's hinterland can be characterized 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). Herrenberg consists of a historic core with a fragmented urban fabric at the urban fringe. The historic center is in particular affected by individual motorized traffic due to planning decisions and implementations in the past. A collector road goes directly through the historic core where the traffic of three highways is merged. Thus, this area is exposed not only to high traffic volumes but also to environmental pollution by emissions. In order to solve this urban challenge, the city of Herrenberg is currently developing an integrated mobility plan (IMEP 2030), which will serve as the guideline for the mobility development over the next 15 years. This process is supported by civic engagement. Until now, nine different traffic scenarios have been developed and tested. We used IMEP 2030 as a test application for our Digital Twin to approach a novel way for enhancing collaborative planning processes.

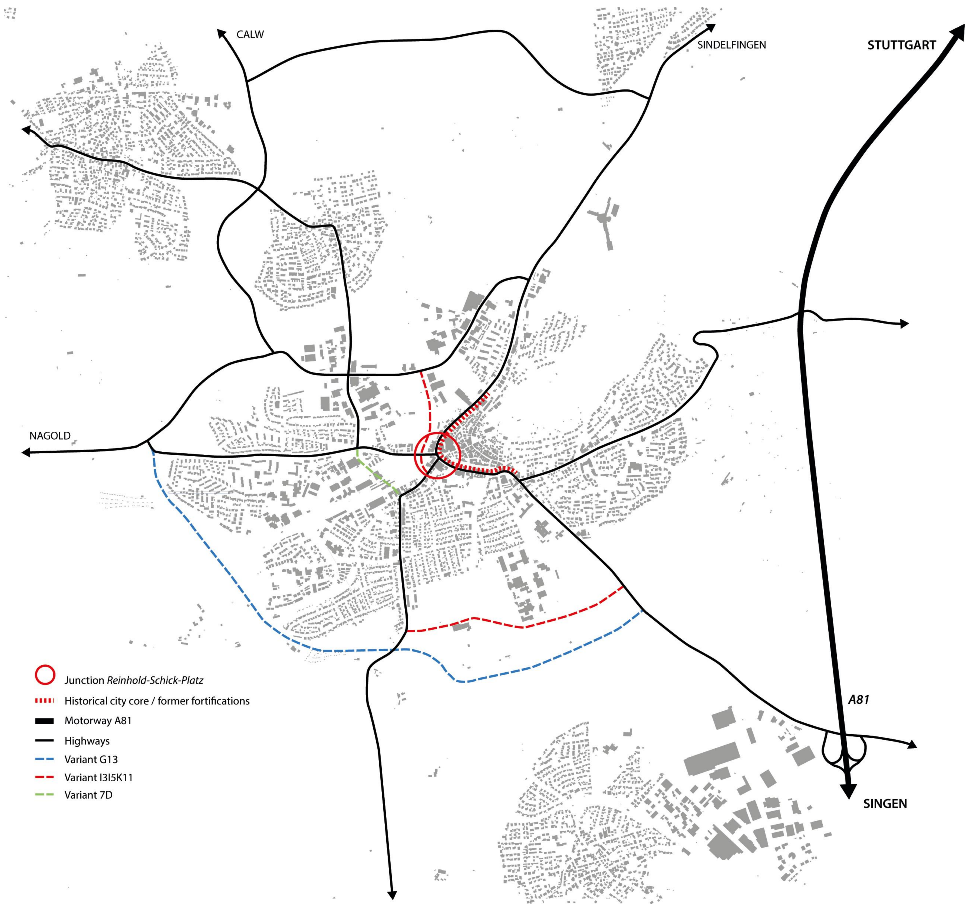

Figure 1. Figure-ground diagram of Herrenberg including the high ranked street network and 3 traffic-planning scenarios.

3. RESULTS

3.1. COLLABORATIVE VISUALIZATION AND SIMULATION ENVIRONMENT

COVISE is an open source modular visualization system, designed to support collaborative visualization 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 2).

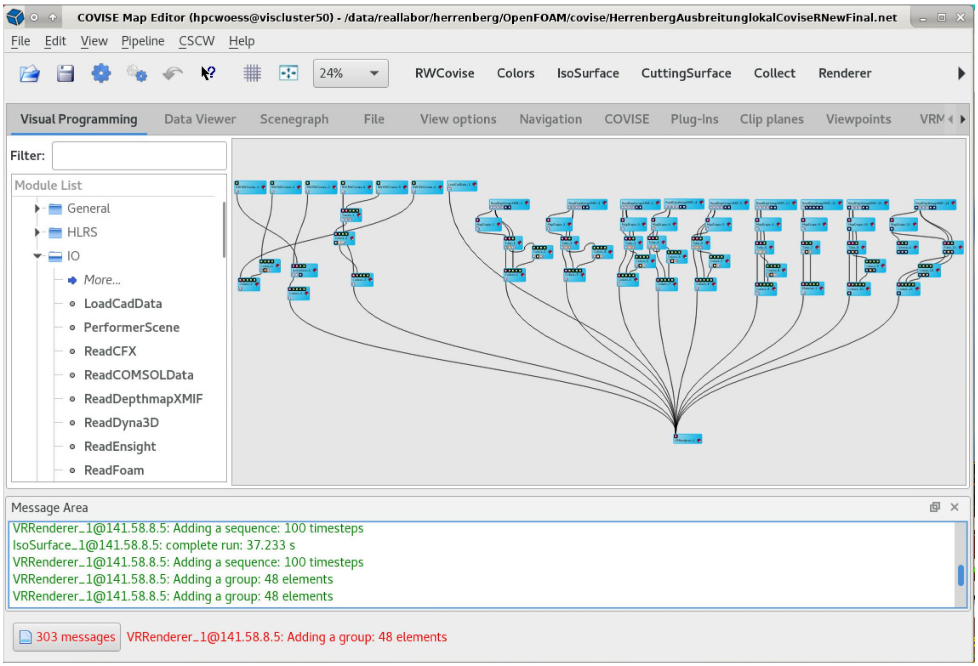

Figure 2. COVISE desktop user interface: Visualization pipeline of the “Herrenberg” dataset.

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 visualize 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 visualize 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 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 visualization modules thus cutting surfaces and streamlines can be interactively placed anywhere within the city to analyze the airflow. Color maps or e.g. the size of tubes representing space syntax results can be visually and graphically adjusted to one’s liking.

3.2. COLLABORATIVE PLANNING

Figure 3. NACH analysis of three traffic planning scenarios and the current situation in 2D.

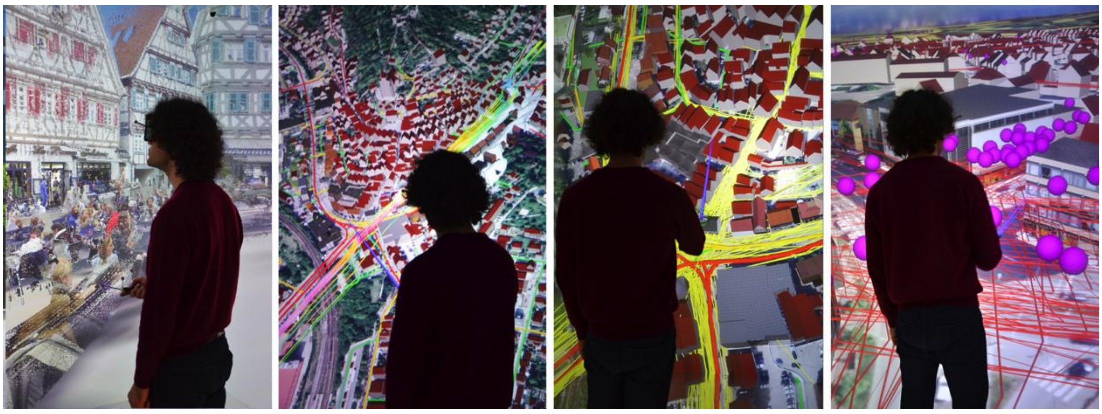

Figure 4. Stereoscopic visualization in the CAVE: a) Visualization of the current situation with the help of point clouds in scale 1:1, walking-mode; b) Visualization of space syntax NACH analysis in 3D-VR linked to data of particulate matter and airflow analysis in big scale and flyby-mode; c) Overlay of space syntax analysis and movement patterns; d) Movement patterns combined with other VGI data collected with the mobile application.

The use of a Digital Twin based on VGI and crowdsourcing for civic science fits well into Arnstein's ladder of citizens' participation as 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.

For the participatory process we used stationary as well as mobile virtual reality environments. The mobile version consists of 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 (https://www.hlrs.de). 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 milieus, in particular kids, youth 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 marginalized groups that are commonly not included into urban planning citizen participation.

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 organizations. In total, approximately 300 participated using the stationary VR environment and approximately 700 participants using the mobile VR.

Figure 5. A group of young citizens using the CAVE during a participatory process at HLRS.

With the support of a sociologist, a questionnaire was developed and we gathered 40 responses with an age from 16–80. The respondents have 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 visualization in form of a polarity profile but as well as open questions relating to the perceived use and eventually missing information. Thus, we collected quantitative and qualitative data. Based on this survery, we wanted to find out about the users' acceptance regarding the Digital Twin and Virtual Reality versus conventional instruments used for participatory processes.

The results showed that all in all, the experience in the Virtual Reality environment was apprehended very positively: The Digital Twin respectively its representation in VR was perceived as very beneficial and interesting. Also visual evidence was very well accepted. 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 (ibid).

Clarity and transparency are seen as major advantages. These user expectations are important when it comes to interaction between administration and citizens and in this context to 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.

Figure 6. Citizens of different age during a participatory process on-site using a mobile VR (3D back projection).

4. CONCLUSIONS

In this paper we set out to present the development of a Digital Twin involving space syntax. It summarizes our development of a Digital Twin, which until now is novel in the field of urban planning. We used a variety of techniques and methods such as 3D modeling, space syntax, urban mobility simulation, wind simulation, people's movement patterns, stationary activity data and qualitative data to configure the Digital Twin. For our pilot application we chose the 30,000 people town of Herrenberg in Germany. It entails areas with high traffic volume and pollution. This gave us the opportunity to test a series of scenarios and potential solutions and furthermore to evaluate their impact 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.

The use of space syntax was especially meaningful as it served as basic analytical model acting as a platform combining a variety of quantitative and qualitative data. Notably, the emission data linked to the airflow simulation were coupled with the NACH mean value for neighbouring street segments in the length of 60m-100m. It needs to be mentioned that the geo-referenced 3D space syntax visualization has its misfit, as it does not present a 3D analytical approach. A 3D space syntax application would be useful *inter alia* for Digital Twins.

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 centered 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), but also at smaller scales. The case study of the Digital Twin described here forms just one piece in the big puzzle.

In summary, for our future research, we plan to validate our findings with regard to participatory, ergo democratic, planning and design for consolidation of herein presented research and furthermore to improve the Digital Twin as mentioned above. Validation and consolidation of our research will help to support the future development of Digital Twins in urban science. This in turn, enhances democratic decision-making for smart, sustainable cities.

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