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Transformative Research in Digital Twins for Integrated Urban Development:

Two Real-World Experiments on Unpaid Care Workers Mobility

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ABSTRACT

Integrated urban development can serve as a cross-sectoral planning concept to manage processes of transformation in urban systems towards sustainability and resilience. At the same time, urban digital twins are being implemented with increasing frequency in urban planning. They can be used to foster such transformations and to make improvements that are more adequate regarding the complexity of urban systems than mere efficiency boost. In this article, the authors discuss how they try to support such change by applying transformative research methods, such as conducting real-world experiments based on prototyping and testing digital tools. The article illustrates how they use the development of urban digital twins in Hamburg, Germany as a field of intervention with the aim of achieving broader usage by and representation of marginalised groups that are typically overlooked in such technology and in urban planning itself.

KEYWORDS

Integrated Urban Development, Mobility, Real-World Experiment, Transformative Research, Urban Digital Twins, Unpaid Care Work

INTRODUCTION

In view of current challenges for urban planning, such as migration, segregation, gentrification, demographic change and extreme weather events due to the climate crisis, the transformation of cities towards sustainability and resilience seems necessary (UN Habitat, 2022; Elmqvist

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et al., 2019). The concept of integrated urban development (IUD) serves as a comprehensive basis on which decision makers and planners, especially in European cities, can manage the necessary transformation processes for urban systems, aiming to meet local challenges with a common good-oriented, multi-stakeholder approach (Ministers responsible for urban matters of the European Union, 2020). However, when this concept is put into practice, numerous challenges arise. Among other demands, IUD requires different departments of the city administration to work together, to involve citizens in planning processes to a greater extent than usual, and to find intersectoral solutions for complex problems in order to develop and jointly implement tailored solutions (Heinig, 2022, p. 18; Beckmann, 2018; Kotzebue 2016).

To deal with such challenges, digital technologies are becoming increasingly important in urban planning. Their growing usage, manifested, for instance, in the development of urban digital twins, is characterised by a knotty relationship between smart city projects and enhanced urban resilience and sustainability. On the one hand, a focus on efficiency, pursuit of profit and proprietary technology in smart city projects hinders the development of resilience principles, such as redundancy, diversity and adaptivity (Berbés-Blázquez et al., 2021) and oftentimes overlooks social aspects of urban planning. On the other hand, the deployment of digital technology could ultimately also contribute to increasing urban resilience and sustainability, as examples of social digital twins show (Degkwitz et al., 2020; Ravid & Aharon-Gutman, 2022). It is thus up to the people commissioning, developing, implementing, and managing such technology to find best practices in their application.

In this contribution we describe and reflect on how we as researchers use one of Germany's largest smart city projects, Connected Urban Twins (CUT), as a field of intervention to actively engage in urban transformation processes supplementary to the process of knowledge production (Bergmann et al., 2021). This approach implies putting the normative aspects of our work up front and describing how we seek to actively support the project's goal of promoting IUD. We intend to develop and promote digital resources for the Hamburg twin that enable the representation of overlooked and thus underrepresented groups in the city's digital planning infrastructure. The focus of this paper is on the process and means of our transformative research, rather than on the process of knowledge production and its results. We showcase our approach by discussing two real-world experiments (REs) in Hamburg, Germany, which we carried out to test two digital tools in their ability to support IUD: one for storytelling and one for data collection.

To give a cross-cutting example from the realm of IUD, as well as to test and apply the digital tools, we chose the use case of unpaid care workers' mobility. Recently the COVID-19 pandemic revealed the importance of care work for ensuring society's ability to reproduce itself and for people to help each other. As Bauhardt (2004, p.117 ff.) and Gabauer et al. (2022, p.4 ff.) point out, care can be seen as a requirement for the sustainability and resilience of urban systems. While the formal sphere of care work received much attention, especially at the beginning of the pandemic (Dowling, 2021, p. 207 ff.; Kunstmann, 2020), the much larger share of unpaid, informal care workers (family caregivers and parents of small children) continued to be left to their own devices (see, e.g., Beach et al., 2021; Fieselmann et al., 2022) in their traditionally and structurally based invisibility (see, e.g., Bauriedl, 2013, p.121). Mobility planning, on the other hand, is a topic that is often tackled with a technology-centric approach in urban digital twins (Ferré-Bigorra et al., 2022), but that approach often excludes the needs of care workers (Spitzner, 2020, p.16 ff.; VCD, 2021; Bauhardt, 2004, p.121 ff., 2007, p.301 ff.). To raise awareness of this situation among decision makers in the administration and advocate for taking the mobility needs of marginalised and overlooked groups more into account in urban planning decisions, we prototyped and promoted the two digital tools mentioned above. Through this effort we wanted to support IUD in Hamburg with a view to increased urban resilience and sustainability.

THEORETICAL BACKGROUND

Urban Digital Twins and Their Transformative Potential for Integrated Urban Development

The concept of urban digital twins is one example of how emerging digital technologies are being promoted to enable a more integrated development of cities in the future (Ferré-Bigorra et al., 2022). Many city administrations aim to develop, consolidate, and 'stack' their digital assets in a digital twin of the city (Cureton & Dunn, 2021). Such interconnected computational systems typically build upon varying sources of spatial data, citywide sensor networks, and other software modules that allow for the simulation of urban systems, thereby creating a digital replica of the real system (Batty, 2018). A common characteristic of digital twins is the existence of a 'physical' and a 'digital' realm which influence each other via some sort of reciprocal data flow (Marcucci et al., 2020). As a fairly new concept that is currently put into practice, urban digital twins provide a unique potential for transformation, as their functionality and architecture is still up for debate (Fuller et al., 2020).

Scholars increasingly advocate for 'multiple models' (Batty, 2021, p.1) and 'different kinds of twins' (Arcaute et al., 2021, p.1) to capture the complex reality of urban processes. Urban digital twins would be based on a common reference system (i.e., an urban data platform) and provide multiple modules that could be used for varying use cases to create multiple instances of urban digital twins (Al-Sehrawy et al., 2021; Knezevic et al., 2022, p.120; Schubbe et al., 2023). The backbone of such a modular concept of urban digital twins is common standards to exchange data between physical objects, the city's data infrastructure, and data analytics/simulation modules. This conceptual understanding of urban digital twins could then help cities to better cope with the increasingly complex task of governing and managing urban systems in the face of current challenges.

Although the concrete design and configuration choices of urban digital twins vary, multiple scholars point out that the main driving force behind such developments is technology centred and promises to enable more efficient forms of urban governance and planning (Allam & Dhunny, 2019; Nochta et al., 2021). Often the complexity of the underlying urban system is thereby reduced to measurable and unidimensional indicators that can be algorithmically optimised (Hudson-Smith et al., 2023). As Ferré-Bigorra et al. (2022) found in their review paper, many urban digital twins exist or are under development to model traffic flows, building stock, energy efficiency, sewage systems, etc. However, given the properties of complex urban relations, such approaches often fall short of including social aspects of a city (Arcaute et al., 2021; Dembski et al., 2020). It seems questionable to what extent urban digital twins that do not incorporate relevant social subsystems contribute to IUD.

Unpaid Care Work in the Urban Planning Context

Unpaid, or informal – as contrasted with formal, employment-based – care work refers to family and volunteer work for others and for oneself. This category includes child-rearing, health care, educational, nursing, and household activities, e.g., cooking, cleaning, or looking after children (Winker, 2021, p.20; Brückner, 2010, p.43 ff.). Estimates put the value added of unpaid care work in Germany at around one billion euros per year, accounting for around 56% of all working hours (paid and unpaid). These workers' scope is therefore significantly larger than the total gainful employment of all employees combined (Winker, 2021, p.21; BMFSFJ, 2020, p.10).

In the domain of unpaid care work, mobility is an essential dimension. Considering the importance of unpaid care work in urban systems, scholars in the critical feminist discourse since the 1980s (e.g., Dorhöfer, 2003) highlight that urban infrastructure in a Western context, specifically in Germany, was planned by, and is largely planned for, persons who are gainfully employed full time, who historically were predominantly men (see, e.g., Crompton, 1999, p.201 ff.). When looking at, for example, road infrastructure planning or the planning of public transport in the course of the reconstruction of German cities after World War II, it becomes evident, that both are primarily designed for commuting

for employment (to the workplace in the morning and back in the evening), in accordance with the urban planning concept of spatial-functional separation that has been idealized since the time of *The Athens Charter* (see, e.g., Le Corbusier, 1962).

In contrast to one-dimensional commuting patterns, the mobility patterns of unpaid care workers are complex and fragmented, e.g., when doing the daily shopping or accompanying children or elderly family members. Accordingly, the requirements for mobility (for instance, in terms of safety, accessibility, or availability) are different (Spitzner, 2020, p.16 ff.; VCD, 2021; Bauhardt, 2004, p.121 ff., 2007, p.301 ff.; Flade, 1999, p.137 ff.).

This largely 'androcentric' (Bauhardt, 2004, p.121) concept of urban and transportation planning, which represents only half of reality and, moreover, neglects the complexity and interconnectedness of the object of 'care' (the relationship between production and reproduction), can be considered neither sustainable nor fundamentally suitable for urban planning (Bauhardt, 2004, p.121; Kern, 2021, p.45 ff.; Jurczyk, 2021; Beebeejaun, 2017). Following the concept of IUD, it is therefore necessary for authorities like social, transport, and urban development departments to increasingly address the concerns of care workers and support them in their everyday lives with cross-sectoral solutions. Since there is a lack of data about the mobility concerns and barriers of that specific group (Spitzner et al., 2020, p.77 ff.; VCD, 2021), it is necessary on the one hand to collect such data and on the other hand to visualise this data, in order to make these problems visible and to be able to adequately and meaningfully communicate the concerns of those affected to policy-makers and planners.

METHOD

Experimentation in Real-World Labs

In sustainability science several research methods exist that build on an interventionist role for researchers in their fields such as living labs, transition experiments, urban transition labs, and niche experiments. With the help of these methods, researchers aim to implement practices for change that are appropriate for both the investigation of and the push towards resilience and sustainability (Folke, 2016; Olsson et al., 2014). With regard to urban development, such research 'needs to be grounded in the realities of city-level actors. It must address how local governments and bureaucracies as well as civil society and people's movements operate and interact and how space for transformative change can be created' (Friend et al., 2016, p.68). Taking this need into consideration, so-called real-world labs have been increasingly implemented, especially in German cities (Räuchle et al., 2021). Emerging from social science research about sustainability, real-world labs offer an investigative and operative research method in which transformation processes and their actors are observed and to some degree influenced (Bergmann et al., 2021).

Therefore, these researchers must align their actions with normative principles and attempt to steer transformations accordingly. Following these normative principles, they should make calculated interventions in physical and social spaces with the aim of expediting and gaining a better understanding of transformation. These interventions can be conducting workshops with different actors to develop joint solutions, testing new technologies in a specific urban context, or making temporary changes of infrastructure, e.g., temporary bike lanes on traffic routes or closing of car traffic. With this approach, researchers take on both an observant and an influential function: They coproduce knowledge together with relevant actors and actively participate in the fashioning of the investigated processes to foster and support transformations. Results should be concretely applicable for the relevant transformation actors in a particular context (these actors can be politicians, decision-makers in administrations, managers, consumers, etc.). Therefore, so-called transformation knowledge should be generated, which must be socially robust in the sense that it directly contributes to solving real-world problems on a practical level within a specific process and (Wanner et al., 2018; Wuppertal Institute for Climate, Environment and Energy, 2022).

The central research instruments within the framework of real-world labs are REs. This approach follows '[t]he basic assumption […] that experimenting and learning-by-doing is important not only to initiate change, but also to arrive at a better understanding of transformation processes per se' (Schneidewind et al., 2016, p.10). Accordingly, real-world labs are the spatial and temporal frame for preparing, carrying out, and evaluating real-world-experimentation. Thus, such experimentation goes beyond simple trial-and-error approaches. REs build upon scientific assumptions to foster transformations purposefully in cooperation with relevant actors, who shall be identified by the researchers in order to initiate mutual learning processes, building trust and laying the ground for common action. Real-world interventions and knowledge production ought to be linked methodically. Therefore, often several consecutive REs take place, which build on each other and, at best, extend the previously gained knowledge (see, e.g., Ziehl, 2021).

Research Design and Questions

For our research we used Hamburg as a real-world lab to investigate barriers and success factors related to the implementation of planning-related software and to draw conclusions about the city's ability to transform by means of digital technology. Therefore, several REs were conducted in Hamburg, which built upon each other. The first two real-world experiments, which we discuss in more detail in the following chapter, were dedicated to the topic of unpaid care workers' mobility. They were run under the project name 'FairCare Verkehr. Initially, no specific topical focus was present for our REs. Since we were free to choose from a wide range of possible use cases, it was crucial to pick a cross-cutting case from the realm of IUD that would be suitable with regard to our research questions:

1. How can social processes and phenomena that are often overlooked in urban planning and digital twin development be made more visible through digital tools?
2. How can the concerns of marginalised groups be taken more into account in planning processes by means of digital tools?
3. How should digital tools be designed to support actors from the fields of politics, administration, civil society, and science in their initiatives aimed at urban transformation?

Besides the case chosen to examine these questions, the focus of the two REs was on two prototypes we designed to become a part of the city's data-governance structure as digital tools for the Hamburg twin: one for data storytelling (Urban Data Narrator – DaNa) and one for data collection (Urban Data Collector – DaCo).

The first real-world experiment (RE1) took place from mid-October to early December 2021 under Coronavirus restrictions. It consisted of (1) a six-week coding phase in close cooperation with a private software development company and (2) a one-week testing phase of the prototypes at touch tables together with unpaid care workers. Since we, as relatively young researchers, were mobilising participants mainly from our own personal networks because of the Coronavirus situation, it was mainly parents caring for their own children who participated. The research team conducted 15 test runs and facilitated them in individual sessions. After the data collection, short interviews were conducted with the participants and recorded as audio files. RE1 ended with (3) a digital public presentation of the tools and the preceded testing phase.[1]

The second real experiment (RE2) built on the first one and addressed the same questions and case, but it was also characterised by differences in terms of the tools, the process, and the topic: A mobile version was added to the data collection tool to reach a wider range of participants. In addition, we worked closely with an association representing unpaid care workers caring for disabled relatives, which meant that the participants of RE2 were primarily caregivers of physically impaired people or representatives of the association. RE 2 took place from mid-June 2022 to the end of January 2023. (1) It started with a city walk together with care workers as a kickoff for (2) a two-month phase of mobile data collection from the end of July to the end of September. [2] This phase was accompanied

by a citywide public relations campaign to mobilise a larger number of affected residents to enter data using the mobile version of DaCo. A total of 63 contributions were posted with approximately 150 data points.[3] There were also several hundred page views, but without data entries. RE2 ended with (3) a multi stakeholder workshop at the end of January 2023.

The Real-World Lab of Hamburg and the City's Urban Digital Twin

Hamburg, which we used as a real-world lab for our transformative research, is a city-state and the second largest city in Germany with a population of around 1.8 million. Tax revenues are relatively high, which enables the administration to implement an integrated digital strategy for urban development (see, e.g., FHH, 2020). Today Hamburg is among the leading cities in Germany in terms of digital data infrastructure and governance (Bitkom, 2022). One of the key projects for expanding and strengthening the city's digital infrastructure is the Connected Urban Twins (CUT) project, which we used as our field of intervention.

CUT aims at developing open standards with the explicit goal of replicating them in other German cities and thus connecting the different instances of urban digital twins. The project is a cooperation between the German cities of Hamburg, Munich, and Leipzig and one of the flagship projects of Germany's digital strategy.

The CUT's definition of urban digital twins is close to the definition of multiple instances of digital twins mentioned in chapter Urban digital twins and their transformative potential for IUD. They are understood as task-related compositions of digital resources whereby a multitude of twins can exist per city (Knezevic et al., 2022, p.120; Schubbe et al., 2023). The modules for each instance are derived on the basis of subject-specific criteria and responsibilities or accountabilities of the underlying planning topic. The project's vision is to represent the city digitally and enable what-if scenarios for IUD (CUT, 2022).

As of now, the core digital resources of Hamburg's urban digital twin are at least threefold. First, the city's self-developed and self-hosted Urban Data Platform (UDP is based on open standards of the Open Geospatial Consortium hosts and organises Hamburg's increasing quantity of data. Second, the city's self-developed and open-source web GIS client, Masterportal, allows for the addition of multiple 'portals', or instances, to the UDP. These portals provide a certain core functionality and can additionally integrate third-party add-ons for visualisation, analysis, and simulation purposes. Third, the digital resources necessary for the creation of what-if scenarios – i.e. running large-scale coupled simulation models – is yet to be created.

Research Agency and Process

In our roles as researchers and actors of the CUT project, we aimed to foster transformations in the realm of IUD in Hamburg by means of digital twin technology and processes. Therefore:

1. We developed digital prototypes and tools, that will become fully functional modules of Hamburg's digital twin.
2. As our main calculated interventions we promoted and tested prototypes and tools at presentations and in workshop settings in collaboration with CUT project partners, other administrative staff from the City of Hamburg, and selected representatives of civil society organisations, which we considered relevant with regard to the implementation of tools in Hamburg's data-governance structure.
3. We reflected on the transdisciplinary working process from a socio-technological perspective to generate knowledge with regard to our research questions (see chapter Research Design and Questions).

Knowledge about tools and prototypes developed in the course of the REs is to be centred around their usability, acceptance by stakeholders, technical deficits, long term applicability in planning processes, etc. By taking on an active role in these processes, we were able to gather many direct

insights simply because we could draw from firsthand experiences, discussions with involved actors, meeting protocols, etc. At the same time, the acceptance for the application of the prototypes and tools should be created among the stakeholders to enable and support their implementation into the digital twin infrastructure.

We designed the prototypes and tools ourselves, on the basis of our experience with digital tools and infrastructure for urban planning and our normative assumptions about how a transformation process of urban systems towards sustainability and resilience can be promoted with the help of digital tools. A key assumption was that a digital development which pays no regard to social processes could have non-sustainable effects and decrease urban systems resilience, at least concerning social aspects such as equity, accessibility, and empowerment of vulnerable groups (Ravid & Aharon-Gutman, 2022; Degkwitz et al., 2020; Allen et al., 2020; Meerow & Newell, 2016). For this reason, we followed our research approach in particular by trying to make the Hamburg twin infrastructure more integrative for social processes in terms of their representation as well as their collaborative data collection. We considered this focus crucial for a transformation towards sustainability and urban resilience, as social aspects often are not sufficiently taken into account when digital twins are developed and used for decision making in urban planning.

Furthermore, we assumed that strengthening the role of civil society within collaborations with official actors and integrating local citizen knowledge into planning decisions is critical to foster transformative change. Many citizens and initiatives advocate for marginalised groups to be heard by decision makers and to participate in ongoing debates about solutions and governance for a transformation towards sustainability (Frantzeskaki et al., 2018, p. 285). This is why, from our point of view, tools for Hamburg's twin technology should expand existing forms of collaboration between citizens and the administration, which are so far primarily deliberative in nature, such as the city's Digital Participation System (DIPAS) (see, e.g., Weber & Ziemer, 2023, p.133; Thoneick, 2021). Thus, it was one of our goals to strengthen the role of citizens beyond deliberative planning practice, so that they could participate in urban development practice in a more self-determined and self-initiated way by applying digital technology (see, e.g., Cardullo & Kinchin, 2018; Noveck, 2015, p.2 ff.).

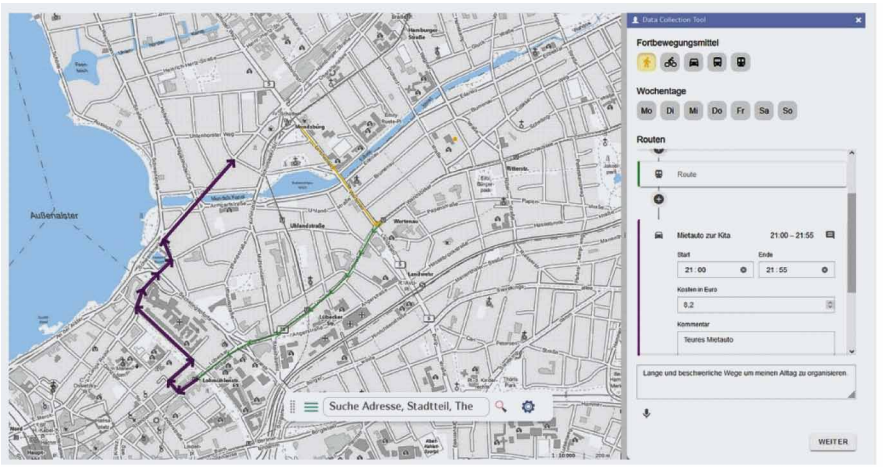
However, our goal was not to conduct a broad-based process of citizen participation in governmental decision-making processes ourselves. Rather, we wanted to test our tools in a specific transdisciplinary environment with administrators and citizens, so that the tools – if they became part of the digital twin infrastructure in the future – (1) could contribute to making official planning and decision-making processes more inclusive, (2) could help to create a more accurate basis for decision-making by collecting and providing specific data and (3) could help to enable citizens to make contributions to urban development themselves by collecting data in a self-determined way and creating as well as publishing their own data stories. Therefore, we prototyped two specific tools, which we describe in the following section.

Urban Data Collector

The primary focus of urban digital twins on physical infrastructure issues and the exclusion of unpaid care work from large parts of societal discourse lead to data gaps regarding the specific mobility behaviour of unpaid care workers (Spitzner et al., 2020, p.77 ff.; VCD, 2021). If such data existed, one could potentially utilise it for more integrated and common good-oriented urban planning processes. Since, so far, no official means exists for citizens to independently collect data or coproduce data sources, we identified the need to prototype such an application.

The core functionality provided by the Urban Data Collector (DaCo) is the capability to draw detailed trip itineraries on an instance of the Masterportal, as shown in Figure 1. The tool was designed as an add-on for the Masterportal. The data entered via this web-GIS client is supplemented with additional information such as means of transport, time spent, and costs. In addition, it is possible to record personal annotations on everyday problems, peculiarities, or suggestions for improvement as

Figure 1. Screenshot of the Urban Data Collector for RE1 (Note: Users are able to input sociodemographic data, various kinds of daily mobility routines with features such as costs and duration, and various annotations of points, lines, and polygons of interest. In addition to the text input, it is also possible to send voice messages.)



text or audio comments that are directly or indirectly related to the recorded paths. Special places of interest, areas, or obstacles can also be selected and commented on. Furthermore, each user has the option to provide further background information about themselves and the person they are caring for. All data was stored on a secured university server and guarded with appropriate information security. Only project team members could access the sensitive data provided.

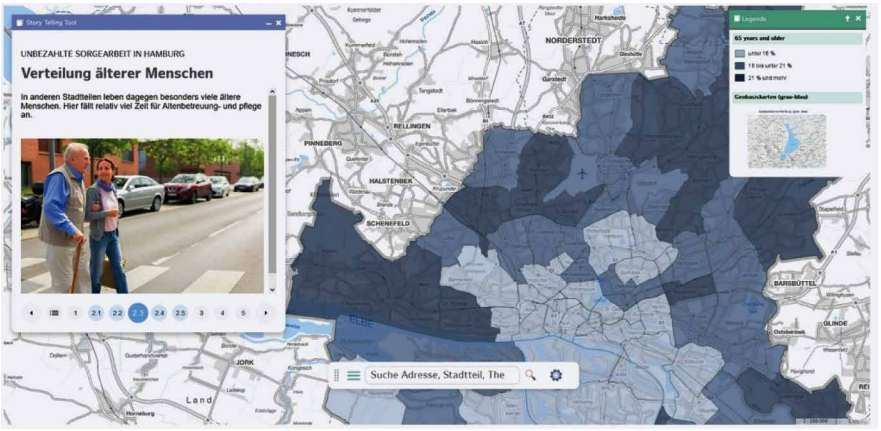
Urban Data Narrator

To contextualise the tool for data collection and thereby counteract the information deficit on the topic of unpaid care work, we identified the need to convey such information in a meaningful way and narrate urban data. Important requirements for the tools were a seamless connection to the DaCo and a connection to Hamburg's urban data platform from a technical and usability point of view. The urban data narration tool that resulted from these considerations is a Masterportal add-on that can be used to augment georeferenced datasets with various media, such as text, images, and videos in a multistep story. In using the narration tool, information and more descriptive visualisations can be added to the largely abstract map display. The georeferenced data of the web-based map is thus contextualised and complex relationships are rendered more easily comprehensible for users not accustomed to working with geospatial data. As shown in Figure 2, users click their way through a story, and with every chapter of the story, the underlying datasets displayed on the map, the zoom level, and the map centre can change accordingly. At the same time, users are still able to interact with the underlying map, to zoom in on a specific area or feature, and to toggle layers that suit their interest. Additionally, the Urban Data Narrator (DaNa) includes the functionality to create stories via a graphical user interface and a 'what you see is what you get' editor.

First Real-World Experiment

With the completion of these tools, the data collection phase of RE1 started. Both tools were tested on the City Science Lab's (CSL) touch tables with invited care workers. The detailed nature of the mobility data made it necessary to have a facilitator accompany and provide professional support for the collection process. In individual sessions the DaNa was used to introduce the topic of the RE1 – the mobility of unpaid care workers – to the participating care workers in the form of a previously

Figure 2. Screenshot of the Urban Data Narrator for RE1 (Note: The tool can be used to both create and view stories composed of multiple steps, data layers, text, images, and other media. At each story step, users can independently navigate and investigate the underlying urban data on the map.)



developed data story, and DaCo was used to create and store datasets on the participating care workers' mobility patterns and their sociodemographic information (see Figure 3).

After one week of data collection during the on-site workshops, a hybrid public online presentation of the tools and the initial results was held in the City Science Lab. Approximately 45 people from different disciplines and backgrounds (including public administration, civil society organisations, urban planning, and city science) joined the event online, which was conducted in a local setup similar to a TV studio. Being the first public outreach after the initial prototyping and testing, this event was central in creating awareness and a foundation for future cooperations with selected civil society organisations relevant to the research case.

Figure 3. Participants of the on-site data collection at the City Science Lab (Note: During 15 individual workshops, we collected thick data on the mobility patterns of invited unpaid care workers and conducted interviews to improve the tools (Source: City Science Lab))

Second Real-World Experiment

The focus of the second real-world experiment (RE2) was on collecting data on obstacles in urban areas that restrict the mobility of caregivers who look after physically and mentally impaired people. The decision to focus on this topic was partly due to the cooperation with AllipA (Allianz pflegende Angehörige Interessengemeinschaft und Selbsthilfe e. V.)[4], which had become aware of the research activities and was to represent an important multiplier with its network in civil society.

To address the need for guided data collection, DaCo was optimised for use on mobile devices, and the data structure was simplified. In particular, the process of entering trips was simplified (so that there would be no predefined mask for specifying times, fares, etc.). In addition, in the new version, each entry could be annotated with a photo and an audio comment. These adjustments to the tool were intended to make the tool more intuitive and accessible for stakeholders to report obstacles in the urban space.

RE2 started with a kickoff event at which, besides the CSL and AllipA, stakeholders from civil society and, most important, participants who were affected by unpaid care work were present (see Figure 4). Besides being a means of collecting valuable data points, the event proved central in raising awareness of the topic, DaCo, and our research. The tool was then shared via the AllipA network and received good coverage from the local media. The tool was also presented at an event that was centred around the topic of dementia. The official data collection stopped after a period of two months. Compared to RE1, in which data collection took place over a period of one week, RE2 was intended to last significantly longer in order to generate a larger dataset. Because of limited human resources and the need for subsequent data analysis, the time period could not be unlimited either, which is why a period of four months was given.

RE2 ended with a workshop made up of 18 participants: 8 from a science background, including the research team; 4 from an administration background; and 6 from civil society. The participants discussed the following questions regarding DaCo: (1) functionality and accessibility of the tool, (2) suitability of the data to reduce barriers in Hamburg, and (3) long-term anchoring of the tool in Hamburg's administration and civil society.

A practical result of the experimentation process is the integration of DaNa into the data-governance structure in Hamburg. As a module to optimise and extend the City's official digital participation-tool (DIPAS) it can be used by the planning department to communicate conditions and the intention of official urban planning processes publicly (FHH, 2023). In contrast, DaCo has not yet been integrated, but the Authority for Transport and Mobility Change as well as the Authority for

Figure 4. Participants' kickoff event for RE2 (Note: Cooperating with the 'Alliance of caring relatives,' we organised a city walk where we kicked off a data collection phase with an adopted tool (Source: City Science Lab))

Labor, Health, Social Affairs, Family and Integration in Hamburg aim to build on both the tool and the network that derived from the real-world experiments with the aim of addressing and improving the accessibility of urban spaces in Hamburg for physically impaired people.

Transformative Research Means

With our research on digital twin technologies and their potentially transformative impact framed by the topic of unpaid care workers' mobility, we aimed to support IUD in Hamburg towards increased resilience and sustainability. Therefore, we deployed various interlinked research means in connection with the two REs. These will be discussed in the following section on a practical level and on the basis of our experience within the ongoing research. Wherever limitations of the individual means were prevalent, we describe those limitations.

Developing Convincing Software

Developing and testing tools that were convincing in the sense that actors from administrations and civil society would promote their implementation in the official data governance was the key transformative means within our research. By anchoring our technical developments in Hamburg's twin infrastructure, we made these developments available for processes of IUD for employees of the administration, civil society organisations, and citizens. This technical integration of our tools in the web GIS core of Hamburg's digital twin represented an absolute necessity for our desired dissemination. In order to maximise the transformative effect of our software, however, our actions as researchers had to go beyond the mere provision of open-source applications. To convince stakeholders, it was important to test the tools in practice with members of the administration and civil society using the example of unpaid care work. This was a central point of our work, as both tools not only represent technical innovations for Hamburg's twin infrastructure, but are also designed for digital cocreative work and data communication processes. By gaining knowledge about their possible use and promoting the cooperation of heterogeneous stakeholders from civil society and administration in digital urban planning, we again aimed at maximising the tools' transformative character.

Intervening in Multiple Roles

In many cases, researchers took on several roles in REs, such as workshop facilitators, scientific experts, project managers, etc. Thus, transformative research processes could easily lead to highly challenging situations, conflicting roles, and the management of activities unusual in scientific practice. This aspect of the research required a high level of reflexivity, agility, and creativity. With regard to the REs we carried out, we understood our role primarily as 'enabler[s] for innovative products and services' (Wanner et al., 2018, p.107) as we developed and tried out tools to foster transformation. Through this approach we aimed to achieve impact in real-world processes in addition to our more traditional roles of researchers as knowledge producers and science communicators. This goal required us to act not only as project managers for the software development, a role that included the conceptualisation of the tools and an agile coding sprint, but also as facilitators for the testing phases together with unpaid care workers.

Creating Strong Images and Media Attention

External communication and public visibility are of great importance for the success of a RE in order to generate attention (including attention within politics and administration), expand networks, and reach key actors (Welling et al., 2022, p.20 ff.; Bergmann et al., 2021, p.556). Transformative researchers therefore might have to take on other important roles, such as being content creators and public relations managers. We created a multimedia data story to contribute to increased attention among our partners in the administration for unpaid care workers and their needs as an example of how important social groups are easily overlooked and marginalised in urban planning. Furthermore, we produced a short film about RE1, which should serve not only to provide documentation but

also to present our work to the public and to project partners (see footnotes 1 and 2 for links to the videos). Later, we released a short film to kick off RE2, which we linked to a small media campaign to call for participation. For both videos it was important that they created strong images and met the requirements of social media communication. Their spread via media channels and networks (Hafen City University, City Science Lab, etc.) led to increased interest from local newspapers and television. Managing these media requests (being available for interviews and filming) again took time away from knowledge production. Because of the public nature of media coverage, a substantial simplification of the scientific aspects of the research led to the public presentation of research aspects and aims as affirmative statements. In this context we did not act as scientists, but rather practised 'marketing' of our research. Such exposure can lead to the external questioning of the scientificity of a project and the research (see, e.g., Köglberger, 2019, p.93 ff.). However, from our point of view, the effort was worthwhile, as it led to an expansion of our network and fostered outreach to potentially interested actors for participation in the data-collection.

Selecting a Strong Use Case

The selection of the use case was by no means an easy process and took us multiple weeks of researching, discussing, generating ideas, and discarding them. Nevertheless, we emphasised the need to find a convincing use case for administrative and civil society actors in the first place, a need which we considered relevant to the implementation of DaCo and DaNa in Hamburg's data governance structure. Technology that is developed as an end in itself lacks a concrete need for its application and thus, we argue, cannot drive urban change. We view the current shift from the technology-centred smart city paradigm towards people-centred smart cities as a confirmation of the importance of selecting convincing use cases. Second, we consider widely overlooked issues with daily relevance for affected communities to have a high transformative potential. In our opinion, these issues are key to the support of civil society and thus to the search for collaboration partners, since an alignment of mutual interests is formed (Schneidewind et al., 2016). Third, topicality proved to be a key dimension, since it connected the issues with a broader public audience by leveraging a policy window. In our case, we found the COVID-19 pandemic to be a magnifying glass for the longstanding structural invisibility of social system components in general and unpaid care work in particular. Fourth, the chosen case needed to be an urban theme that bridged disciplines to include a variety of stakeholders from civil society and public administration, as should be the case with IUD. Last, since tools developed in the CUT were in almost every case based on georeferenced data, we wanted to pick a case with large gaps in the available data. This was crucial to highlight the necessity for our cocreative data collection tool and the corresponding processes. In its implementation, it was especially important to collect, store and handle the sensitive data with care, as well as to prevent misuses with appropriate information security measures.

Building Transdisciplinary Networks for Multi-Stakeholder Collaboration

Finding modes of collaboration with multiple locally engaged stakeholders across domains and disciplines is crucial for obtaining specific information, aligning interests, and ultimately creating agency for transformative research (see, e.g., Weber & Ziemer, 2023, p. 110). In our case, we could build upon trust generated during past projects of the City Science Lab (CSL) among key stakeholders in the City of Hamburg. The CSL was founded in 2015 and has since developed several tools to improve the city's digital infrastructure for urban planning in close collaboration with the administration. Additionally, the CUT project was designed in such a way that cross-institutional collaboration is not only intended on paper, but also reflected and promoted in its project structure. Leveraging these preconditions, we presented the possibilities of our tools to a variety of project partners, decision makers from the City of Hamburg, and actors beyond. It was especially on-site meetings with ample time for informal exchange that helped in promoting our tools. Furthermore, we created new collaborations with civil society, which meant working together with volunteers in an

honorary capacity accompanied by fewer resources and, understandably, times of limited availability. We thus had to adapt to uncertain time frames. Additionally, expectation management from our site was vital to the collaboration. At times it was challenging to clearly communicate the limited agency and extent of our research scope to participants from civil society. Nevertheless, we were still able to collaborate with civil society to find potential means of transformation and to raise awareness of the mobility needs of unpaid care workers and define these needs for city administrators.

CONCLUSION AND OUTLOOK

To better address the needs of marginalised and overlooked groups in the decision making procedures of urban planning, we prototyped and promoted two digital tools in collaboration with selected citizens and public administration. Hereby we aimed to support IUD in Hamburg for the purpose of increased urban resilience and sustainability within the framework of our ongoing transformative research. The two REs discussed in this paper were based on our assumption that visibility of and data on marginalised groups like unpaid care workers are necessary prerequisites for a transformation of urban systems towards sustainability and increased resilience. We are aware that our scope of action in the CUT project can provide at best only a little support for the necessary changes. Ultimately it is outside our power to decide if and how tools that we promote become part of administrative data-governance structures. This will be done by CUT project partners within Hamburg's administration on the basis of the tools' practicality and concrete demands. Furthermore, as we have shown, our transformative research had to cope with additional challenges (e.g., the researchers' having multiple roles and a large work load in fields unusual for researchers) and limitations (e.g., dependence on media for outreach). Thus, a successful contribution to sustainable transformation is not guaranteed. Nevertheless, our roles as transformative researchers in the CUT project enabled us to influence the decision-making process by providing convincing software, demonstrating demands with the help of specific use cases, and fostering collaboration among relevant actors from science, civil society, and administration.

With regard to future research and interventions within the CUT project, central questions are how tools can be open to citizens in the long term for the public collection, communication, and modelling of data, as we identified its exclusive use by public administrators as a possible risk to the transformative potential of our tools. While the public sector is a key user group, we aim to ensure that tools are also open and usable for potential drivers of transformation from other fields, such as social associations or citizen initiatives, that have a critical perspective on the urban planning of Hamburg's administration. Other main tasks are the structured derivation of transformation knowledge from the research process as well as the evaluation of our actions as researchers and of our ability to support transformation processes in the long term. The latter seems to be one of the main challenges in conducting real-world labs, because of the complexity of urban system transformation and the time needed to realise measurable impacts. However, results will be published and shared with our project partners to support mutual learning and a conversation about their progress towards the overall goal of the CUT project, the improvement of IUD.

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ENDNOTES

1 A video documentation of RE1 can be found here: https://www.youtube.com/watch?v=iqi-qff7fCg
2 A video documentation of the RE2 kick off can be found here: https://youtu.be/mZnqFQLCXWc
3 A data story with the plotted data can be found here: https://re2-results.cut.hcu-hamburg.de/mobility-results/
4 English: Alliance caring relatives interest group and self-help. A civil society organisation of family caregivers in Hamburg with the aim of mutual assistance and joint representation of interests towards politics and administration.

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Rico Herzog studied environmental engineering, industrial engineering, and engineering and policy analysis at the Technical Universities of Darmstadt and Delft. With a background in spatial planning and in computational modelling and simulation of complex socio-technical systems, he conducts research revolving around urban digital twins and their contribution to a sustainable urban transformation. His additional academic interests lie in public value conflicts in urban planning and in serious gaming approaches.

Till Degkwitz studied business informatics and political sciences at the Leuphana University Lüneburg. Since 2009 he has worked as a freelance software developer for ad hoc-analytical systems in business intelligence. His current focus is processes of data analysis in urban data platforms and transforming forms of participation in the context of emerging information and communication technologies.

Martin Niggemann studied social sustainability and demographic change at the Institute for Applied Social Sciences at the FH Dortmund and studied social pedagogics at the Catholic University in Paderborn and Cologne. Before working at the HCU, Martin worked in quartier management and as a research assistant at the FH Dortmund. In his work, he concentrates on socio-cultural dimensions of urban studies, the qualitative surveying of urban spaces, and research on the impact of digital technologies in the urban context. He joined the SmartSquare research project at the City Science Lab in January 2018.

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