

Making Complex Environmental Data Accessible Through a Multi-User Perspective: Learnings From the COUP System

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Submitted: 30 April 2026 **Accepted:** 10 August 2026 **Published:** 28 October 2026

Issue: This review is part of the issue “Citizen-Centric Urban Planning Through Participatory Sensing Data and Digital Tools” edited by Gamze Dane (Eindhoven University of Technology), Bernd Resch (Interdisciplinary Transformation University Austria), and Peter Zeile (Karlsruhe Institute of Technology), fully open access at <https://doi.org/10.17645/up.i530>

Abstract

Growing urban complexities and urban planning increasingly rely on participatory approaches based on digital technologies to democratise access to information and enable citizens to shape healthier and more inclusive cities. However, traditional GIS interfaces often exclude non-expert stakeholders, thus limiting genuine collaboration. A promising alternative is tangible user interfaces (TUIs), which combine intuitive physical interaction with computational geospatial analysis. Still, knowledge of diverse stakeholders' experiences remains limited. This study reviews the implementation of COUP (Cockpit for Collaborative Urban Planning). It is a hybrid tangible-digital interface integrating physical city models with real-time environmental simulations. The system enables users to manipulate physical building models while immediately observing wind comfort, noise propagation, and pedestrian flow through projected visualisations. The presented use cases from the past six years span diverse contexts and stakeholder groups, from the use of the interactive table in deliberation processes and expert discussions, the development of immersive reality components, to the remote use of the web interface and its application in higher-level educational contexts. The findings provide empirical evidence and multiple perspectives on the system's capacity to support data-informed, collaborative urban design and advance understanding of how tangible geospatial interfaces can translate complex environmental data into actionable planning insights accessible to diverse stakeholders. This review offers recommendations on how participatory digital tools can empower users, shape urban spaces, and consider multiple stakeholders' needs while supporting evidence-based environmental decision-making essential for building healthy, inclusive, and climate-responsive cities.

Keywords

environmental simulations; geospatial visualisation; participatory urban planning; tangible user interfaces; user experience

1. Introduction

Urban transformation increasingly demands planning approaches that address complexity. Rather than replacing traditional methods, digital tools complement planning by supporting transparency, participation, and cross-sector collaboration. Planning support applications and online participatory platforms improve stakeholder engagement by facilitating access to spatial information and enabling more inclusive decision-making processes (Glaas et al., 2020; Lin & Benneker, 2021). The integration of visual or creative elements—such as photovoice—allows community perspectives to be embedded early in planning (García-Esparza & Nikšič, 2024). Environmental considerations also benefit from digital innovation. The visualisation of green infrastructure, simulation of climate adaptation, or enabling hybrid public engagement formats contribute to informed and participatory responses to urban resilience challenges (Kousis et al., 2021; Mattijssen et al., 2024; Venter et al., 2021). The need to adapt tools to various ecological contexts is vital, as highlighted in studies on urban restoration and environmental simulations (Canuto et al., 2024; Pigliautile & Pisello, 2020).

To be effective, digital systems must be designed with usability, accessibility, and institutional integration in mind. Scholars emphasise the need for inclusive interfaces, cross-disciplinary platforms, and mechanisms that support transparent spatial decision-making (Hanan & Carhart, 2025; Skogheim & Atkinson, 2013). Emerging approaches that incorporate AI or real-time GIS-based collaboration further underline the potential of digital tools to manage complex urban dynamics while ensuring citizen trust and engagement (Du et al., 2023; Raymond et al., 2025; Rinner & Bird, 2009). Digital technologies are not only reshaping how cities are planned, but also defining which stakeholders can participate in the planning processes. Their design and deployment must remain attentive to local context, societal needs, and institutional frameworks.

For complex urban planning scenarios requiring multi-criteria evaluation, the embodied interaction paradigm makes geospatial analysis more approachable and participatory processes more effective (Maquil et al., 2015). Recent implementations extend table-top tangible user interfaces (TUIs) with advanced capabilities. Integration with real-time environmental simulations enables immediate feedback on design decisions, such as microclimate impacts, noise propagation, or accessibility. Some systems incorporate motorised physical elements that respond dynamically to simulation outputs, creating tangible feedback loops that communicate computational results through physical movement.

This review of applied use cases for an interactive tangible-physical planning tool, COUP (Cockpit for Collaborative Urban Planning), across various contexts and users highlights its strengths, adaptability, and technological characteristics. The discussion focuses on how different planning contexts and stakeholder groups shape the requirements and evolution of tangible participatory planning systems, and on the design lessons that emerge from deploying a tangible decision-support system across diverse multi-stakeholder contexts over several years. The learnings from the past six years outline future development potential and contribute to the discussion of implications for collaborative planning approaches from the perspective of digital tools.

2. Background

2.1. Participatory Planning

Participatory approaches have long been studied as a multi-faceted element in shaping cities and societies, influencing science, planning processes, governance structures, and the legitimacy of societal interventions (Healey, 1997; Schrögel & Kolleck, 2018; Weinberger et al., 2021). Rooted in traditions of deliberative and collaborative planning, participatory approaches have enabled citizens to contribute local knowledge, articulate needs, and contest development priorities. Early foundations of participatory planning trace to influential theoretical and practical contributions, such as the concept of advocacy planning (Davidoff, 1965) and the ladder of citizen participation (Arnstein, 1969), which advocate integrating multiple groups into decision-making processes. Krumholz and Hexter (2022) advanced an equity-oriented approach that prioritises fairness and redistribution in urban policy. John Friedmann's transactive planning model highlighted mutual learning between planners and citizens through direct engagement (Sanyal, 2018). In parallel, the experimental "Non-Plan" proposed by Reyner Banham and colleagues challenged centralised control by advocating deregulated development (Barker, 1999). Similarly, Giancarlo De Carlo's work in Urbino demonstrated participatory design in practice (Charitonidou, 2021), while Jane Jacobs's community-based approach and vision of the "diverse city" underscored the value of bottom-up urban complexity (Schubert, 2019). Together, these contributions laid important groundwork for contemporary participatory approaches in urban planning.

With the rise of digitalisation, however, the nature of participation has undergone significant transformation, integrating advances in information technology and social media (Krivý & Kaminer, 2014) as well as unexpected societal shifts in the post-Covid-19 era, where participatory planning in times of physical distancing required reconsideration (Frahsa et al., 2025; Unger & Lee, 2023). In this regard, digital platforms and tools have expanded engagement opportunities by lowering barriers to entry, enabling real-time interaction, and broadening the spectrum of participants. At the same time, these developments introduce new challenges, including digital inequality, data governance, and the fragmentation of public discourse, reshaping both the possibilities and limitations of participatory urban planning.

2.2. Implications for Citizen-Centric Urban Design

Digital approaches such as public participation GIS (PPGIS) tools have demonstrated stakeholder engagement by making geospatial information accessible to non-experts, enabling citizens to contribute local knowledge and preferences that inform planning decisions (Kahila-Tani et al., 2019). Yet, successful implementation of digital participatory platforms extends beyond technical capabilities. Effective engagement requires careful consideration of interface usability, equitable access across diverse user groups, and integration within existing institutional planning frameworks (Brüggemann et al., 2023).

These hybrid-technology innovations align with broader trends toward "smart data" in geoinformation science, transforming raw geospatial information into actionable insights through interactive, contextualised representations (Hesselbarth et al., 2025). Computational fluid dynamics (CFD) models now generate comprehensible street-level wind-comfort analyses and air-pollution dispersion patterns at fine spatial resolutions (Ridzuan & Ujang, 2023). Noise propagation models following standardised acoustic principles

enable realistic assessment of sound exposure from traffic and other urban sources (Dutilleux et al., 2010). Digital-twin technologies facilitate real-time integration of sensor data with simulation models, supporting dynamic urban management (Wang & Wang, 2024). Nevertheless, translating geospatial data and scenario simulations into actionable planning insights remains challenging when map representations and imagery fail to convey spatial relationships intuitively or contextualise environmental implications clearly for a broader audience.

2.3. TUIs for Urban Planning

TUIs have emerged as a promising paradigm for making complex geospatial data accessible in participatory planning contexts. By combining physical objects with digital computation, TUIs leverage intuitive physical manipulation while maintaining the analytical capabilities of computational systems (Hornecker & Buur, 2006; Ishii & Ullmer, 1997). Early implementations like Urp demonstrated the potential of tangible tabletop interfaces, enabling architects to manipulate physical building models while receiving real-time feedback on shadow patterns and wind flows (Underkoffler & Ishii, 1999). In urban planning specifically, CityScope pioneered LEGO-based tangible interfaces combined with agent-based simulations to evaluate urban design scenarios (Alonso et al., 2018). Colour-coded LEGO bricks representing different land uses are placed on a grid-based interactive table, triggering simulations across metrics including mobility patterns, energy consumption, and social dynamics. CityScope has been deployed internationally, including Hamburg, Andorra, Shanghai, and Guadalajara, demonstrating the fundamental scalability of tangible planning tools. However, its grid-based approach constrains spatial flexibility, limiting its ability to represent irregular urban geometries and organic planning processes. Beyond large-scale urban systems, tangible interfaces have been explored for specific planning domains. The PlanningLab framework combines tangible markers with real-time accessibility analysis, enabling evaluation of pedestrian routing and barrier-free design (Maquil et al., 2015). The PaKOMM project demonstrates a hybrid environment integrating tabletop interfaces with virtual reality (VR) and augmented reality (AR) components for open space planning, supporting both synchronous and asynchronous collaboration through flexible device setups (Postert et al., 2022). UrbanSim incorporates tangible building blocks with land-use and transportation models, demonstrating the feasibility of coupling sophisticated urban simulation frameworks with accessible participatory interfaces (Waddell, 2002).

3. The COUP System

The development of the COUP system is closely linked to the evolving requirements of urban transformation processes. Climate change, digitalisation, and societal challenges such as participation, social equity, and resilient infrastructure are placing increasing demands on how urban development is designed and communicated. These shifts call for new forms of participation, data integration, and visualisation of complex planning dynamics. COUP was first developed for the Kleiner Grasbrook district project in Hamburg. The goal was to create a hybrid tool that connects traditional physical city models with digital technologies. The result was a mixed analogue-digital system that combines projections, geospatial data, and simulations (e.g., traffic, noise, accessibility) to support dialogue among planners, stakeholders, and the public. By making spatial relationships tangible and data more accessible, COUP aimed to lower participation barriers and improve understanding of urban planning challenges.

3.1. Genealogy of the Tool

COUP converges several development streams in data-based modelling, digital city research, and interactive media that frame new practices of collaborative planning and decision-making (Weiner et al., 2024). The system's conceptual and technical DNA has evolved significantly, as COUP has been continually researched, developed, and applied to new use cases since its inception. In order to grasp pathways, key inheritances, and potential path dependencies that have determined the evolution of the system in the past, and will certainly influence it in the future, the next paragraphs will briefly outline its provenance and genealogy—so to say the “genetics” of the tool (Figure 1).

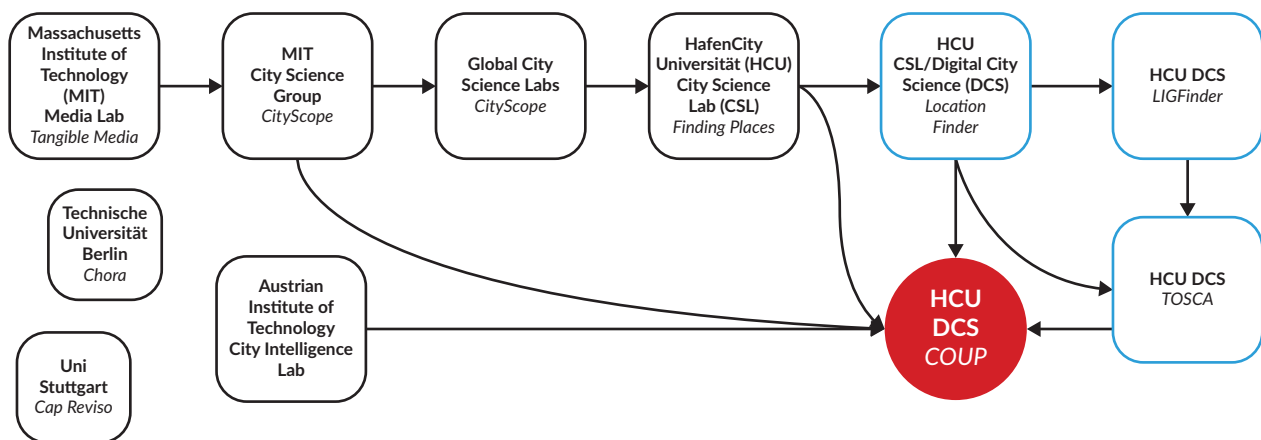


Figure 1. Technological and institutional pathways of COUP’s development, with external partners in black and sister projects developed within the team in blue.

Basically, the technological and institutional evolution of COUP relates to the academic work and technical products of research groups at two scientific institutions, the Massachusetts Institute of Technology (MIT) and the HafenCity University Hamburg (HCU). Nearly a decade ago, the Changing Places/City Science Group within the MIT Media Lab proposed the CityScope interactive modelling technology as a concise system applicable to real-world urban planning and development challenges (Alrashed et al., 2015; Hadhrawi & Larson, 2016). To do so, it built on long-term research on human-machine interaction and tangible media, pioneered by other MIT Media Lab groups (Ishii & Ullmer, 1997). As part of its strategy to disseminate and promote the technology, the MIT group established several satellite city science labs with institutions such as the HCU Hamburg, Tongji University Shanghai, Taipei Tech, and the state of Andorra.

During this institutional collaboration, HCU’s City Science Lab applied the CityScope technology in the Finding Places project (2015–2016) to address the challenge of allocating housing for the large number of international migrants coming to Hamburg at the time (Noyman et al., 2017). This foundational project spun off several follow-up activities and derivative technologies. The specific use case of location finding led to a set of conceptually and technically interrelated GIS-based tools and spatial analytics with applications in the context not only of Hamburg’s municipal ground property management with the platform AGORA (Analytics for Ground Property and Real Estate Assessment) and the LIG Finder tool (Dally et al., 2024), but also of global development aid in Ukraine, Ecuador, and India (Moleiro et al., 2023; Mukherjee et al., 2024) with the Location Finder tool and the open GIS platform TOSCA (Toolkit for Open and Sustainable City Planning and Analysis). A second prominent stream focused on providing tactile spatial interaction with spatial models for

urban planners and architects. The specific case of the urban development of the “Kleiner Grasbrook”—a new city district in Hamburg—and the cooperation with local development agencies in charge of this large-scale project provided the opportunity to redesign the CityScope technology into a comprehensive new system (Figure 2) that works in accord with the demands of urban design competitions, decision-making processes, and project communication (López Baeza et al., 2021).

Forming a comprehensive urban simulation framework, COUP not only acknowledges and builds upon the research work of other institutions working in the field of interactive urban modelling (TU Berlin, Stuttgart University, ETH Zürich) but also integrates, within its new modular system architecture, external components such as the multi-language based environmental simulations provided by the City Intelligence Lab at the Austrian Institute of Technology, now the Vienna-based spin-off *infrared.city* (Noennig & López Baeza, 2025). This modular yet highly integrative system design supports future technical extensions of COUP, e.g., new simulation modules, and its applicability to a broad range of use cases, e.g., reconstruction and recovery planning in Ukraine.



Figure 2. COUP Interactive Table Interface in its latest state of development.

3.2. System Design

As a digital platform, COUP currently combines three interactive user interfaces with various analysis modules in a shared back-end, enabling users to examine relevant target qualities of planning projects. The first interface, a web application, lets users access the system remotely without any physical setup. The second is a physical interactive model table (Figure 2), where users can collaboratively edit designs and test planning scenarios. Technically, the tangible table combines a physical 3D city model with a digital projection and sensor layer, consisting of accurately scaled, 3D-printed buildings mounted on a surface tracked by an overhead projector and an underlying camera system. Physical and volumetric input elements,

“tangibles,” represent planning parameters such as land-use types or density scenarios, and are uniquely identified via marker tracking. The third interface enables VR interaction, allowing users to experience an immersive perspective of the urban design to enhance deliberation and decision-making.

The back-end processes inputs from the web interface or model table and feeds simulation results back into the interfaces as heatmaps or animated flow visualisations. Five analytic modules are currently available, calculating traffic noise, solar gains, pedestrian wind comfort, stormwater runoff and pedestrian flows. A central feature of the system is the real-time link between input and feedback: When users place or move tangibles, the projected content responds immediately, displaying isochrones, land-use overlays, or noise exposure directly on the model surface or web UI.

3.3. Technical Components and TUI

COUP builds on the CityScope foundation but addresses the grid-based limitation through free-form, tangible interaction, enabling stakeholders to place building models anywhere on the planning surface without grid constraints (López Baeza et al., 2021). The system is built on the 3D gaming technology Unity (versions 2019 to 2023 LTS) to render the digital planning surface and manage real-time interactions. Physical building models are 3D-printed at scales of 1:250 to 1:300, placed on a modular aluminium table structure with an acrylic glass surface onto which a rear-projection foil is mounted. A 4K short-throw laser projector positioned above the table projects content directly onto this surface, including onto the physical building models themselves (Figure 3).

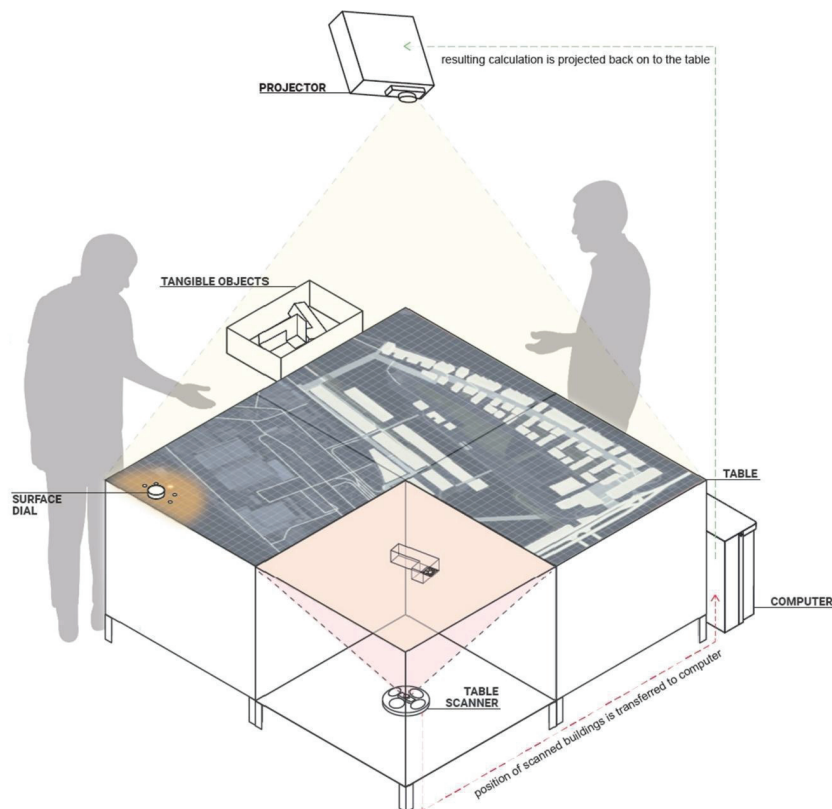


Figure 3. The tangible table as one of COUP's three interfaces.

A Python-based system running locally on the table's computer handles object recognition using optical markers (OpenCV, ArUco) integrated directly into the building models for detection. Intel RealSense D435 cameras mounted beneath the table surface operate in infrared mode, with surrounding LEDs illuminating the markers without visible-light interference. Detected building positions and rotations are transmitted to Unity via WebSocket as JSON-formatted strings carrying real-world coordinates, used both to update the live visualisation and to dispatch simulation requests to an external server, which returns results as a heatmap or animated visualisation rendered onto the planning surface.

The primary tangible input device beyond the buildings model is a Microsoft Surface Dial, connected via Bluetooth, which navigates a circular on-screen menu through which users can select, start, and hide simulations or select individual objects.

3.4. Analytic Modules

The COUP system integrates a modular set of environmental simulation modules, accessible across its three frontend interfaces. The web application currently supports five simulations—pedestrian flow, stormwater runoff, traffic noise, wind comfort, and solar exposure—whilst the tangible table, VR, and extended reality (XR) interfaces provide access to three modules—pedestrian flow, traffic noise, and wind comfort (Holtorf & Noennig, 2025). This distinction reflects a fundamental technical difference: The latter three can be computed in near-real time in response to user interactions, while stormwater and solar simulations rely on precomputed results and are therefore better suited to the web-based dashboard format.

Wind comfort is evaluated using a trained model provided by the Austrian company *infrared.city*, assessing pedestrian-level conditions based on the Lawson criteria. Traffic noise is calculated using the open-source tool *NoiseModelling*, developed by Gustave Eiffel University, with results rendered as heatmaps within approximately 45 seconds. Pedestrian flow is simulated using an agent-based model implemented in the GAMA platform, representing a synthetic population moving through the district according to realistic daily routines.

4. Use Cases

4.1. Kleiner Grasbrook Hamburg: Innovating an Urban Design Competition

The first use case for COUP resulted from a research-based cooperation between university and municipal stakeholders to accompany an international urban design competition. It produced an expandable digital solution for assessing design proposals for the development of a new district: the Kleiner Grasbrook in Hamburg (López Baeza et al., 2021). This case served as a living lab for accompanying scientific research and for the initial validation of the COUP; however, it did not replace the conventional preliminary assessment within the Competitive Dialogue (HafenCity Hamburg GmbH, 2021).

COUP was originally developed and adapted to support the decision-making of two types of users: (a) participating finalists developing their proposals (architecture and landscape offices) and (b) the competition juries mandated for the evaluation of the final proposals. This was the first time the designed analytical modules for environmental assessments were applied to compare three different designs and used for private deliberation and evaluation purposes.

The web instance of COUP was used during the final stage of the competition (Figure 4), where six selected competitors were paired into three teams, each composed of an architecture and a landscape office, and provided with access to an integrated version of their design to analyse environmental impacts in real time. It was consistently emphasised that this should be considered a significant time-efficiency gain compared to consultancy reports, which provide deeper analyses but require considerably more time to deliver.

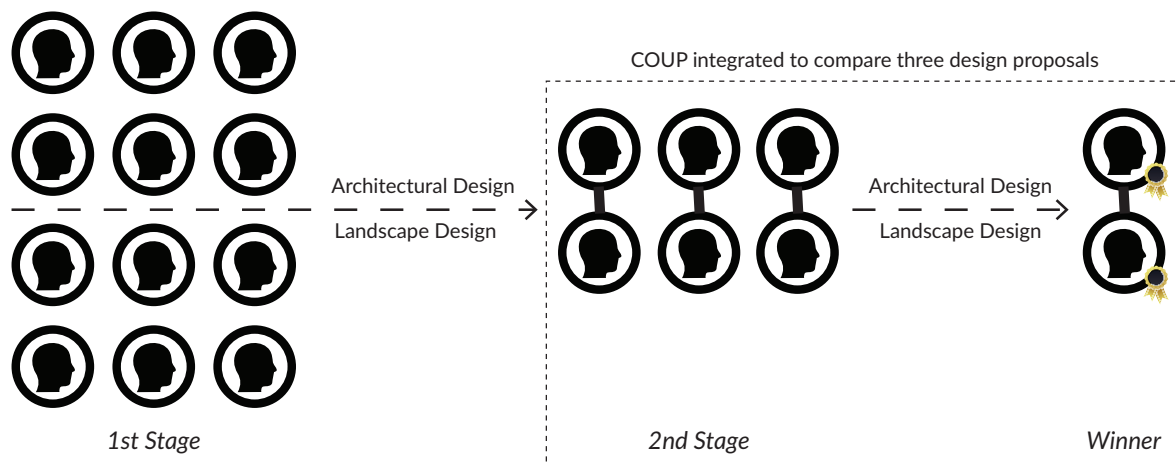


Figure 4. Integration of COUP into the “competitive dialogue” design competition scheme.

Feedback on the usability of the tool was collected in written form via our contracting partner. One proven advantage was the tool’s ability to swiftly provide preliminary analytical results during the design process, allowing designers to receive immediate feedback in early stages of proposal development and helping to optimise both time and deliberation when preparing competition entries. The tool also enabled the competition jury to evaluate proposals more objectively through a unified platform for ingesting individual design proposals and conducting subsequent quantitative analysis. A key weakness was that the data conversion pipeline between commonly used architectural design software and COUP still needed streamlining. Another issue was the limitation of the original grid-based input format, which led to oversimplifications of building shapes. The team addressed both setbacks in subsequent development.

Its hybrid setup enabled designers, project investors, and jury members to engage with the area’s future development in a visually transparent and collaboratively negotiable way. Rather than serving solely as a presentation tool, it functioned as an active dialogue medium—supporting deliberations during the urban design competition.

4.2. COUP-XR: Adding Mixed Reality Experience

COUP-XR was developed as part of a master’s thesis as an immersive extension of the existing deployment for the Kleiner Grasbrook, adding a cross-reality layer to the established tangible table setup. Rather than replacing the physical interface, the system introduced a complementary VR component, enabling cooperative cross-platform interaction: Whilst one or two participants continued to work at the tangible table, a third user could enter an immersive VR environment and explore the Grasbrook district at pedestrian level. The Normcore networking framework facilitated multi-user connectivity, allowing both groups to interact with a shared, synchronised model in real time. All changes made at either interface are immediately

visible to the other side. The two user groups were additionally connected via direct audio communication through microphones and speakers, forming a fully integrated hybrid discussion environment regardless of physical location.

A key advancement over the previous COUP system was the introduction of fine-grained, building-level simulation control. In addition to district-wide planning scenarios, VR users could modify individual building variables, including use type and façade material, with distinct acoustic absorption values that directly influenced pedestrian flow and traffic noise simulations. The system also allowed users to switch between top-down planning views, agent-based ground-level perspectives, and collaborative overview modes. To reinforce the experiential impact of acoustic parameters, the system integrated spatial 3D audio into the VR environment, making the consequences of high traffic volumes and the diminished sound-shielding effect of repositioned buildings perceptible in an immediate, embodied way. The system was evaluated through a structured testing phase involving two to three participants per session, with findings and cooperation dynamics documented and analysed, including user perspectives on cross-reality collaboration in urban planning contexts (Holtorf & Noennig, 2025).

4.3. Matthäikirchhof District Leipzig: Enabling Digital Citizen Participation

Building on the system architecture established for the Kleiner Grasbrook deployment, the adaptation of COUP for Leipzig applied the existing toolkit to a fundamentally different urban planning scenario: the transformation of the Matthäikirchhof, an inner-city district characterised by a mix of existing buildings, heritage-listed structures, and historically significant urban fabric. Unlike the Kleiner Grasbrook project, which involved the planning of an entirely new district, the central challenge in Leipzig was to support collaborative engagement within the complexity of a pre-existing urban environment.

The core simulation modules developed for the Kleiner Grasbrook—including wind comfort, street-level noise, and pedestrian movement—were retained and adapted to the Leipzig context through the integration of localised input data. The physical and technical setup required considerable refinement to accommodate the site's greater complexity. The Leipzig model comprised approximately 125 LOD-2 (level-of-detail) buildings compared to roughly 60 LOD-1 structures in the Kleiner Grasbrook model, and to reliably handle the increased number of trackable objects, the camera-based recognition system was enhanced by applying a mosaic filter. A further advancement concerned spatial accuracy: Whereas the Kleiner Grasbrook setup relied on two reference points for coordinate interpolation, COUP Leipzig introduced a four-point referencing system, substantially reducing positional discrepancies between the physical model and the complementary web application.

The scenario centred on a direct comparison of two planning alternatives for the Matthäikirchhof developed by the city: a complete redevelopment versus a hybrid approach that preserves and refurbishes significant existing structures while integrating selective new construction. The model was deliberately designed to extend beyond the immediate project boundary, allowing users to also explore modifications to the surrounding building stock in anticipation of future planning processes in the wider area.

The system was deployed over a six-month project period through two complementary formats at the Smart City Lab Leipzig, a public showroom for the city's digital urban development. Open-door sessions allowed

members of the public to visit the lab, interact directly with the tangible table, test planning ideas, and provide informal feedback on the spatial implications of different design choices. In addition, one to two dedicated evening events brought together invited participants from the City of Leipzig, local planners, and researchers, who worked with COUP alongside other digital planning tools. Feedback from these sessions was collected informally by the Smart City Lab team and subsequently communicated to the project partners.

Recurring observations from public participants highlighted the tool's capacity to attract attention and lower the threshold for engagement. Users found it playful and approachable, and noted that moving physical building models made spatial experimentation intuitive even for those without technical planning backgrounds. A notable contextual difference from the Grasbrook deployment was the stronger emphasis on traffic and mobility in Leipzig, with participants frequently expressing a desire to modify street layouts and pedestrian and vehicle routes—capabilities that exceeded the current system's scope. Following the six-month development period, COUP has remained in active use at the Smart City Lab Leipzig, where it continues to be deployed in civic engagement events and public consultations.

However, the ongoing use of the installation has also highlighted a practical limitation of the tangible table setup. The system requires regular recalibration and technical maintenance, demanding continued involvement from the development team beyond the original project period. This maintenance burden directly informed the decision to pursue a fully virtual architecture for the subsequent Zhytomyr deployment, eliminating hardware calibration dependencies whilst retaining its core participatory and simulation capabilities.

4.4. Zhytomyr City, Ukraine: Supporting the Development of Recovery Strategies

The COUP case for Zhytomyr was developed as part of the SURPRISE project, an international collaboration between HCU and partner cities in Ukraine to establish cadastral data frameworks based on existing spatial information. The underlying rationale was preparatory. By creating reliable baseline data on building stock and land parcels, the project sought to lay the groundwork for future planning and reconstruction efforts in the event of war-related damage. COUP was integrated into this framework as a visualisation and participation tool, enabling project partners to explore planned development scenarios based on the newly established cadastral data.

As establishing a physical, tangible table on-site was not feasible given the geographical distance, the deployment was built entirely in VR, drawing on components from both the Leipzig case and COUP-XR. The underlying system logic and data structure followed the Leipzig implementation, whilst the multi-user VR infrastructure was carried over from the Normcore-based networking system introduced in COUP-XR. The selected site, an existing district in Zhytomyr chosen by the city's representatives, had been earmarked for urban transformation prior to the outbreak of the war, making it a suitable test case for exploring how digital planning tools could support both pre- and post-conflict planning processes.

The virtual environment encompassed 177 LOD-2 buildings, the largest model footprint across all COUP deployments to date and reflecting the absence of physical table constraints. The immersive environment was grounded in imagery provided by the Ukrainian project partners, lending the virtual space a contextual authenticity reflective of the local built environment. Of the established simulation modules, wind comfort

and street-level noise were integrated, while pedestrian movement simulation was omitted due to insufficient local data.

A key experiential advancement in this iteration was the introduction of a dual-perspective mode: Users could switch between a top-down planning view and an immersive pedestrian perspective, allowing them to move through the district at street level. Lessons learned from the COUP-XR deployment were directly applied, including the addition of a mini-map to aid spatial orientation and improved visual representation of users in pedestrian mode for those remaining in the planning view.

The system was presented at a concluding project workshop held at HCU, attended by 15 representatives from several cooperating Ukrainian cities, combining on-site and remote VR participation (Figure 5). To support continued independent use, VR headsets were provided to the Ukrainian partners, with the multi-user architecture enabling future remote collaborative sessions. Feedback highlighted the tool's effectiveness for building placement and spatial discussion, whilst expressing a clear desire for expanded planning capabilities, particularly regarding green spaces and street layout modifications. After the project concluded, the team remained available for follow-up sessions, though no further joint planning activities took place.

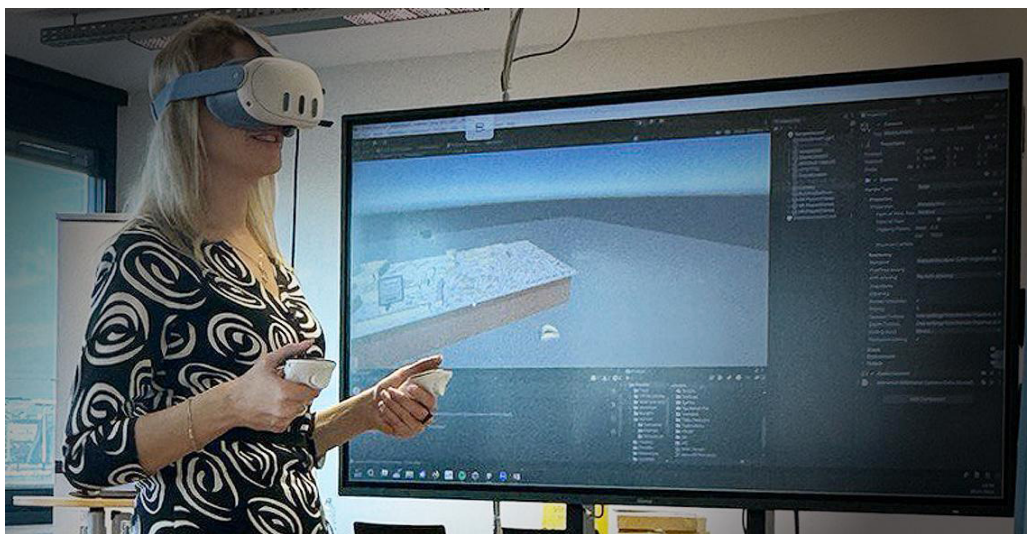


Figure 5. User testing of COUP's VR features.

4.5. Higher Education: Digital Capacity Building and Behavioural Change of Future Planners

Between 2023 and 2025, the COUP system was tested across four academic courses at the HCU, in parallel with ongoing implementation projects. Participants included master's-level students from diverse planning-related disciplines, bringing together varied expertise relevant to collaborative planning. 12 user groups of 58 master's-level students participated in the courses, enabling both individual exploration and collaborative discussion during testing sessions.

Students were progressively introduced to COUP through a structured workflow: Seminar lectures covered the system's hardware setup, development context, and simulation capabilities before any hands-on

engagement. Afterwards, groups familiarised themselves with the tool through free exploration (Figure 6), followed by the identification of specific urban design challenges in the given district (e.g., block development along noise-exposed streets, overshadowing effect from tall buildings). Groups developed planning interventions to address these challenges and tested their proposed solutions at the COUP table. Students worked within the challenge-based learning framework and completed their analytical tasks autonomously in subsequent sessions. Feedback was produced collaboratively at the group level, yielding 12 group reports. This format captured user feedback from collectively negotiated assessments rather than individual perspectives.



Figure 6. COUP Interactive Table Interface used during academic courses.

The findings from this activity demonstrated COUP's ability to make complex geospatial data more accessible and actionable, highlighting its potential to support collaborative planning and decision-making (Holtorf et al., 2026). However, the study also revealed that this potential depends heavily on the system's technical reliability. Data accuracy, computational performance, and the trustworthiness of simulation outputs emerged as critical factors influencing user confidence and adoption. Participants indicated that sophisticated simulation capabilities alone are insufficient; they must be paired with consistent performance and transparent, reliable results to effectively support planning processes.

These findings have important implications for designing tangible planning interfaces. Unlike conventional GIS workflows, COUP is expected to support highly responsive, near-real-time interaction that aligns with users' expectations during collaborative sessions. Achieving this requires improvements in computational efficiency,

the incorporation of progressive visualisation and clear progress indicators during processing, and continued validation of simulation models to strengthen confidence in system outputs.

5. Discussion

5.1. Strengths of the System Across Contexts

The longitudinal deployment of COUP across various contexts over six years reveals a consistent set of capabilities recognised across professional, civic, and academic settings. A systematic evaluation with 58 master's-level students across 12 interdisciplinary groups identified four consensus-level strengths: real-time interactivity (91.7%), collaboration support (83.3%), visualisation quality (83.3%), and multi-parameter integration (75.0%; Holtorf et al., 2026). These findings resonate across the broader use case spectrum documented in this review.

Real-time interactivity was consistently valued throughout all deployments. In the Kleiner Grasbrook competition, architecture firms and jury members could immediately observe environmental impacts of their proposals, compressing lengthy analytical processes into interactive workshop formats. In Leipzig, citizens found the tool playful and approachable, noting that moving physical building models made spatial experimentation intuitive even for those without technical backgrounds. In Zhytomyr, Ukrainian partners similarly highlighted the tool's effectiveness for building placement and collaborative spatial discussion.

These findings are further corroborated by the COUP-XR use case (Holtorf & Noennig, 2025), in which nine participants from urban planning, architecture, and XR-development backgrounds assessed the system. The AR table's user-friendliness averaged 8.3 out of 10, and most participants rated the cross-reality collaboration as useful or very useful. Participants highlighted the immediacy of feedback as a particular strength, with one noting that "you immediately see buildings moving, options for changes are easy to understand and meaningful."

The multi-parameter integration capability proved especially relevant across professional contexts, where planning decisions rarely concern a single environmental factor in isolation. Several users across all deployments consistently valued the ability to assess multiple simulations within a unified interface.

5.2. Limitations and Iterative Responses

Significant limitations recurred across deployments. Data accuracy and reliability concerns emerged as the most widespread issue in the academic evaluation (75% consensus), alongside performance and lag issues (66.7%) and technical instability (58.3%; Holtorf et al., 2026). In the Kleiner Grasbrook competition, the data-conversion pipeline between architectural software and COUP emerged as a key operational weakness. In Leipzig, the requirement for regular recalibration and ongoing maintenance extended team involvement well beyond the project period, a practical burden that reflects a broader challenge for physical tangible interfaces in public-facing settings. In the COUP-XR evaluation, VR navigation and spatial orientation emerged as the most prominent limitation, with participants citing the absence of a mini-map, unclear simulation legends, and controller complexity as specific pain points.

Many of these limitations directly informed subsequent technical iterations. Positional discrepancies in the Grasbrook deployment led to a four-point referencing system in Leipzig. During the Zhytomyr case, the team addressed VR navigation challenges in COUP-XR by adding a mini-map that improved user representation. The maintenance burden of the physical table informed the decision to pursue a fully virtual architecture for Zhytomyr. This iterative pattern reflects a research design logic in which each deployment serves as both application and evaluation, a dynamic visible only when examined longitudinally.

5.3. Context Shapes Requirements

The deployment contexts show how strongly stakeholder composition shapes the demands placed on a participatory planning system. The Kleiner Grasbrook competition demanded simulation credibility and analytical precision from professional users. Leipzig required accessibility and visual clarity above all, serving citizens without planning expertise. Zhytomyr demanded a fully virtual architecture to overcome geographical distance. The academic context reframed the system as both a planning instrument and pedagogical medium.

Across contexts, recurring user requests emerged independently—the desire to save and compare simulation states, incorporate green infrastructure into the planning surface, and extend editable parameters beyond building placement—suggesting genuine unmet needs rather than context-specific preferences.

A recurring theme was also who the system is designed for and who can access it. The COUP-XR evaluation surfaced an instructive perspective: Several participants explicitly noted VR's potential as an accessibility tool for non-expert stakeholders. One participant observed that VR offers “the opportunity for scenario mapping accessible for people and stakeholders with spatial reference frame skill,” whilst another suggested a role division in which AR serves professionals and VR serves citizens. The Zhytomyr case lends further weight to this argument: By enabling remote participation through VR headsets provided directly to Ukrainian partners, the system demonstrated how virtual environments can extend participatory reach beyond the physical constraints of a tangible table, potentially engaging groups who would not otherwise participate in formal planning arenas.

6. Conclusion

This review has presented the development and deployment of COUP, a hybrid tangible-digital planning system, across four iterative implementation cases over six years. Tracing the system's evolution from its origins as a competition support tool for the Kleiner Grasbrook district through to its latest cross-reality and fully virtual deployments, the review has documented how each context has both utilised and shaped the system—informing design decisions, surfacing limitations, and expanding the range of stakeholders and planning scenarios that such tools can serve.

In response to how different planning contexts and stakeholder groups shape the requirements and evolution of tangible participatory planning systems, the evidence presented here demonstrates that context is not merely a setting but an active conditioner for the system's design and utilisation. Professional competition settings demanded simulation credibility and analytical precision; public participation formats required accessibility and visual clarity above all; remote international collaboration necessitated a fully

virtual architecture; and academic deployment reframed the system as both a planning instrument and a pedagogical medium. No single configuration could meet all these needs simultaneously, but the iterative adaptations documented across the COUP deployments reflect this diversity of demand.

From deploying a tangible urban planning system across diverse participatory contexts over several years, three recurring insights stand out. First, the tension between real-time responsiveness as a valued capability and the computational constraints that inevitably limit it is a fundamental challenge for this class of systems, requiring both continued technical optimisation and honest communication of system capabilities to users. Second, iterative deployment is a generative research method: Limitations encountered in one context become the basis for improvements in the next, producing knowledge that no isolated evaluation could yield. Third, a consistent set of unmet user needs—the ability to save and compare simulation states, incorporate green infrastructure into the planning surface, and expand editable parameters beyond building placement—emerged independently across all deployment contexts, pointing to a clear roadmap for future development.

The question of accessibility for non-expert users deserves particular attention as the system evolves. Across its deployment stages, COUP has demonstrated capacity to engage stakeholders with varying levels of spatial and technical literacy—from architecture professionals in Hamburg to citizens in Leipzig and recovery planners in Ukraine. Evidence from the COUP-XR evaluation suggests that VR may play a distinct role: by enabling immersive, pedestrian-level exploration, it offers a form of spatial understanding that does not presuppose familiarity with top-down planning representations. This positions VR not merely as a technical extension of the tangible table, but as a potential instrument for broadening participation to groups who may lack the spatial literacy to engage meaningfully with conventional planning interfaces.

Taken together, these findings contribute empirical grounding to the broader discourse on participatory geospatial technologies. The value of tangible planning interfaces lies not only in their technical capabilities but in their capacity to make complex environmental data legible, discussable, and actionable across diverse user groups. COUP's ongoing development suggests the system will continue to evolve in response to more planning contexts, and that this responsiveness is itself a core feature of its design philosophy.

Acknowledgments

The authors thank all participants in the various workshops, public engagement events, and user studies conducted across the COUP deployments for their time and valuable feedback. Special thanks to contributors who have supported the development of the COUP system over the years.

Funding

COUP Grasbrook was funded by the HafenCity Hamburg GmbH. COUP Leipzig was developed as part of the Connected Urban Twins (CUT) project, funded by the City of Leipzig. COUP Zhytomyr was funded by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH as part of the SURPRISE project. Publication of this review in open access was made possible through the institutional membership agreement between HafenCity University Hamburg and Cogitatio Press.

Conflict of Interests

The authors declare no conflict of interests.

Data Availability

The anonymised feedback data from all 12 user groups are openly available at <https://doi.org/10.5281/zenodo.18195076>. The dataset includes feedback transcripts and participant demographics.

LLMs Disclosure

Claude (Anthropic) was used to assist with grammar editing, style improvement, and reformulation. The authors remain responsible for the content accuracy, originality, and validity of the presented work.

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