UD Co-Spaces: A Table-Centred Multi-Display Environment for Public Engagement in Urban Design Charrettes

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ABSTRACT
UD Co-Spaces (Urban Design Collaborative Spaces) is an integrated, tabletop-centered multi-display environment for engaging the public in the complex process of collaborative urban design. We describe the iterative user-centered process that we followed over six years through a close interdisciplinary collaboration involving experts in urban design and neighbourhood planning. Versions of UD Co-Spaces were deployed in five real-world charrettes (planning workshops) with 83 participants, a heuristic evaluation with three domain experts, and a qualitative laboratory study with 37 participants. We reflect on our design decisions and how multi-display environments can engage a broad range of stakeholders in decision making and foster collaboration and co-creation within urban design. We examine the parallel use of different displays, each with tailored interactive visualizations, and whether this affects what people can learn about the consequences of their choices for sustainable neighborhoods. We assess UD Co-Spaces using seven principles for collaborative urban design tools that we identified based on literature in urban design, CSCW, and public engagement.

Author Keywords
Charrette, collaboration, interaction design, interdisciplinary design, public engagement, sustainability, urban design, user-centered design, visualization

ACM Classification Keywords
H.5.2-3. Information Interfaces and Presentation: User Interfaces, Group and Organization Interfaces

INTRODUCTION
This application paper describes UD Co-Spaces (Urban Design Collaborative Spaces), an interactive multi-display collaborative environment to support complex urban design exercises. Urban design is the process of designing neighbourhoods and larger urban areas. It typically focuses on the relationships of buildings, streets and public spaces to make urban areas functional, livable and sustainable.

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UD Co-Spaces is centered on a multi-user tabletop display that enables stakeholders to collaboratively design the future of a neighbourhood through direct multi-touch manipulation of planning options, interactively explore design alternatives, and cross-check with sustainability indicators in real time during a session. It includes auxiliary wall displays and hand-held individual displays that extend the functionality of the tabletop to better support Arnstein's notion of *engagement* for users [2]. The interdisciplinary project is a long-term collaboration involving a team of human-computer interaction (HCI), computer-supported cooperative work (CSCW), urban design, and public engagement researchers.

Definitions and terms. Our target application is urban design charrettes (or simply *charrettes*), one common method for engaging the public in complex planning for urban design. Charrettes are intensive multi-day processes during which a team of professionals and a diverse set of community stakeholders create a holistic development plan through a series of iterative feedback loops [7, 9, 15]. Charrettes often utilise direct manipulation of physical representations of urban design precedents or *cases*, such as buildings, streets, or parks. A case has information such as its footprint (for a building and its associated surroundings), height, volume, energy usage, and other attributes. A *pattern* is a spatial layout of cases that constitutes a possible urban design. Increasingly, urban design considers sustainability and uses *indicators* such as building occupancy levels, commercial and residential capacities, density, dwelling types, energy usage, land use, jobs, transportation utilisation, walkability indices for neighborhoods, and other measures related to sustainability that help estimate the environmental and social consequences of a proposed urban design pattern. Indicators are calculated based on the spatial layout and attributes of an urban design pattern, often using heuristics derived from urban design models.

In this paper, the term "design" is overloaded. It could mean designing urban environments or it could mean designing environments to support urban design. We try to make clear which is meant each time we use the term, but usually we mean designing urban environments.

Real-world application: the urban design charrette. Charrettes have been characterised as "an impossible problem in an absurdly short time" where the constraints are an essential characteristic of the process [7]. Charrette participants include facilitators, design professionals (architects, urban designers), experts (planners, engineers, scientists), and public stakeholders who have a vested interest in the project. These are our users. In this process, participants explore multiple variables and possible solutions. Charrettes still rely heavily on "hand" drawings completed by design professionals. They often lack rigorous evaluation, particularly in real time. Where digital tools such as GIS mapping have been introduced, they remain expert driven so that non-expert participants remain passive consumers of information [5, 7, 15]. A bottleneck in the adoption of these tools is that software developers are too far removed from the planning environment [17], so they lack important contextual knowledge concerning the diverse interests that steer the interactions of growing numbers of stakeholders. We spent considerable time learning about existing charrette processes and workflows, and the shortcomings of current practice. Our research examines how surface interaction techniques on multiple interconnected displays can better support user engagement in complex processes of urban design during charrettes.

Value hypothesis: surfaces promote engagement. Stakeholders with different knowledge, expertise, and objectives participate in public consultation phases of urban design. Our main goals are: (a) engaging different groups of stakeholders to actively interact with design options, (b) fostering collaboration and co-creation of urban design through the use of touch-based interaction and surface technology, and (c) enabling stakeholders to understand consequences of their choices using simple visual encodings that connect sustainability indicators to urban form.

Design process and principles: domain and user centered. System design choices for UD Co-Spaces were informed by various literature in CSCW, planning support systems, and public engagement. We followed an iterative user-centered process to identify appropriate surface-based interaction tools that promote common ground among stakeholders with various backgrounds and objectives. We examined how different display form factors might increase engagement with both the process and the group. Through our observations of the system in use, we considered which collaboration and visualization technologies enable stakeholders to interactively design solutions and better understand the consequences of their designs. Three major system iterations each added a new display type to UD Co-Spaces to support collaboration and visualization activities identified in formative evaluations.

One challenge we faced was lack of design guidelines for charrettes that address engagement, collaboration, and other domain-specific requirements. Although our system design choices were informed by collocated collaborative visualization guidelines on tabletops [12, 20], we also reviewed literature in urban design and public engagement and adopted principles from Arnstein [2], and Snyder [22] to the narrower challenge of building engaging Collaborative Planning Support Systems (CPSS) for the urban design charrette process.

Based on these principles and our own observations of UD Co-Spaces in use, we synthesised a set of seven principles for urban design charrettes: (1) ***engagement***, (2) ***collaboration***, (3) ***interactive visualization***, (4) ***accessibility***, (5) ***iteration***, (6) ***understanding consequences***, and (7) ***transparency***. In our discussion we describe the principles and explain how the features in UD Co-Spaces work together to address them.

Figure 1. The third iteration of UD Co-Spaces, a multi-display collaborative environment where multiple users can simultaneously interact with 2D maps on a tabletop, with 3D views on the wall, and with two applications on hand-held iPads.

Next best alternative: traditional planning systems. Collaborative and visualization technology can play an important role in increasing public engagement in urban design, but few systems support the complexity and interactivity required for a truly collaborative decision-making process. Many current tools use powerful GIS-based visualizations, however, they are expert-intensive, non-collaborative, and rarely provide real-time feedback because they require significant effort to produce visual encodings of indicators.

Contributions and overview of the paper. We describe UD Co-Spaces (Fig. 1) and the iterative user-centered design process we followed over six years in close collaboration with experts in urban design and neighbourhood planning. We reflect on system design decisions and how multi-display environments can engage a broad range of stakeholders in decision making and foster collaboration and co-creation for urban design. We examine the parallel use of different displays, each with tailored interactive visualizations, and whether this affects what people learn about the consequences of their choices for sustainable neighborhoods. Finally, we assess UD Co-Spaces using the seven design principles that we identified for collaborative urban design tools that target charrette-style processes.

After summarizing prior research on the charrette process in urban design, planning support system software, interactive visualization and collaboration tools, multi-display environments, and guidelines for assessing urban design tools and processes, we describe the iterative development of UD Co-Spaces and its deployment and evaluation through three prototypes. We conclude with a discussion of lessons learned and suggestions for future work to support the charrette process using the framework adapted from the literature.

RELATED WORK

There is a rich body of research in CSCW and tabletop applications for collocated collaboration, visual analytics, and decision making. We focus only on urban design tabletop applications and charrette-style processes where the goals are to provide tools that help users understand the consequences of design choices and promote a sense of empowerment that encourages broad-based public engagement.

Planning support systems. There are many digital Planning Support Systems (PSS) under development that are used to engage the public with long-range decision-making around climate change [6, 8]. Built primarily upon GIS and decision-support tools, PSS are digital systems that integrate spatial and non-spatial analysis with simulation and visualization capacity specifically tailored to the needs and processes of planning-analysis, prediction and prescription [14]. Our goal is to address the challenge of public engagement identified by researchers [11] by providing comparative data about spatial scenarios that is accessible and understandable by the general public.

Interactive visualization. Computers can provide visualization methods to increase understanding, actively engage with lay people, and expand the reach of public engagement processes. The Planning and Urban Design Standards [3] define visualization in this context as "the process of taking abstract ideas or data and translating them into easily understood or interpreted images to enhance planning, urban design and decision-making processes." Visualization tools can display urban forms in two and three dimensions with associated data: computerised versions of traditional maps, perspective drawings, and data plots [1].

Most similar to our work are PSS tools that link and visualize complex information so non-professional stakeholders can better engage and understand long-range consequences of decisions.[1] These PSS support 3D scenario development linked to preset planning parameters, source data customised to location and application, integration of spatial and non-spatial data, trial and error scenario testing, and plan revision. However, many of these tools are suited only to a narrow range of scale (spatial extent) and do not adjust well to other scales. For example, MetroQuest is well suited to study policy questions at the city or metropolitan scale, whereas CommunityViz is better suited to urban form scenarios at only the district scale [8]. The level of expertise needed to use each system varies widely. Some are relatively user friendly, whereas others require significant expertise [8]. For planners to engage and use PSS in their day-to-day work, the systems must be more flexible and adaptable to different circumstances, easier to learn, and better at providing interfaces for the public [14].

Tabletop systems. There has been previous work on collaborative tabletop systems for urban planning [4, 10, 13, 17, 23]. Perhaps best known is URP, from the MIT Media Lab [23]. It is a workbench environment with a tangible user interface that allows urban planners to study how architectural structures will affect light, wind, and other factors that have an impact on urban design. The same group developed Luminous Table [13] to address limitations in URP. Luminous Table is an augmented or mixed reality system that blends digital tabletop objects with physical objects integrating 2D drawings, 3D models, and computational simulations. Physical models of buildings can be placed on the table and they will be recognised by the system and then simulations calculate shadows and wind flows that can be rendered on the table. A 2D drawing can be provided as a background image for the study area.

Multi-display environments. Some research has utilised multiple displays used in conjunction with collaborative tabletops. For example, Wagner et al. [25] developed a mixed-reality system for urban planning using both tabletop and wall displays with physical objects on the table. The objects are only used as tokens instead of being actual scale models of buildings as in Luminous Table [13]. However, the application is more a presentation tool for previously developed urban designs, with little support for interactive design. ETH's ValueLab [10] is a collaborative environment that brings together large interactive displays and visualizations to facilitate public participation in the planning of megacities (what ETH researchers refer to as "Future Cities"). GIS data and visualization software is used to simulate design choices. ColorTable [17] is an interactive round table designed to facilitate communication between diverse stakeholders. It utilises a tangible user interface and tokens placed on the table to represent design elements, such as buildings or streets. It uses a physical map augmented with 2D images and 3D objects to lend the design area more realism. A perspective view of the design is provided by a projected image on a wall display.

Tangible vs. digital. Our goal is different from other systems. We target urban design activities and explicitly focus on user engagement, collaboration, and awareness of design consequences. The collaborative and interactive environments of ColorTable and Value Lab are the most similar to UD Co-Spaces in terms of their goals, which are focused on collaboration and public participation. However, the system architecture of each is quite different from that of UD Co-Spaces: Value Lab relies on GIS data and 3D animations for its visualization needs, while ColorTable's tangible user interface relies on physical tokens to represent design features. Evaluation of the ColorTable revealed "that participants had troubles following long workflows, organizing the number of objects, and interpreting which physical object is linked to which digital counterpart in the case of large differences in size" [17].

The obvious advantages of tangibility are, in our opinion, outweighed by the overhead of providing physical artifacts appropriate to a range of urban settings. Our research provides a totally digital solution, with the possibility of supporting tangible objects in the future. UD Co-Spaces uses external systems as components to provide flexibility and extensibility of geographic areas and building types for planning exercises. Neither Value Lab nor ColorTable incorporates hand-held devices; UD Co-Spaces is unique in this respect.

Principles for engagement in collaborative urban design. Planning support tools have a diverse range of objectives that have their own guidelines. Design charrettes are a specific type of collaboration with unique characteristics such as lim-

[1] Examples of commercial tools include: Community Viz (placeways.com/communityviz), INDEX (www.crit.com/sparc), MetroQuest (metroquest.com), and UrbanSim (www.urbansim.org)

ited time, multivariate data, multiple users with different levels of expertise, etc. These characteristics pose new challenges for designing support tools for this domain space.

While guidelines from collaborative visualization [12,20] address the use of collaborative technology and design of visualizations for multiple users, CPSS requires additional guidelines specific to the domain and to the challenge of engaging various stakeholders in the design process. Engaging stakeholders with different backgrounds, expertise, and expectations is a prominent challenge for design charrettes. Arnstein's widely adopted **Ladder of Public Engagement** [2] proposes an eight-level hierarchy of *manipulation, therapy, informing, consultation, placation, partnership, delegated power*, and *citizen control* to assess the degree of engagement in general settings.

In the context of urban planning, Snyder [22] proposes a 13-point "wish list" for urban design tools including *interactive and usable at multiple levels of expertise*, *accessible and affordable*, *adaptable and maintainable*, *having an open architecture*, *utilising high quality data*, *operating at local and regional scale*, *providing comprehensive coverage and integration of issues*, *supporting impact analysis including short-, medium- and long-term effects*, *engaging citizens and supporting face-to-face interactions*, *visual imagery*, *values, causes, and effects*, *promoting identification of design options*, and *regular monitoring and reporting*. However, there are no specific guidelines in urban design that target all of the requirements for CPSS specific to design charrettes. Based on these principles, and our own observations of UD Co-Spaces in use, we synthesised a set of principles for urban design charrettes that we describe in the Discussion.

ITERATIVE DEVELOPMENT OF UD Co-Spaces

There were three major iterations of UD Co-Spaces, each adding a new display type to support collaboration and visualization activities identified in formative evaluations. For each iteration we discuss key lessons learned during field deployments that affect the final system, including challenges and design rationale.

Iteration 1: A multi-user, multi-touch tabletop. A proof-of-concept prototype on a SMART Technology Digital Vision Touch (DViT) tabletop (91.5cm x 74cm top surface, 65.4cm height, 57.2cm x 42.9cm screen with 1024x768 pixels) ran custom software developed entirely in C# using SMART's Table SDK. The code base had 15 classes, 135 methods, and 4795 lines of code.

Cases and patterns. The tabletop's horizontal form factor provides a natural collaborative platform where individuals can explore options in parallel by dragging cases from a *side bar* (Fig. 2A) along the edge of the display to locations on a 2D map at the center of the display. The side bar has a full set of cases that are colour-coded according to building type and usage. Cases can be moved and rotated at any time. Tapping on a case opens a pop-up window with detailed information (floor area, number of bedrooms, alternate views, etc.). The shared map in the center of the tabletop is the only place to create urban design solutions. This was done to encourage collaborative co-creation of urban designs.

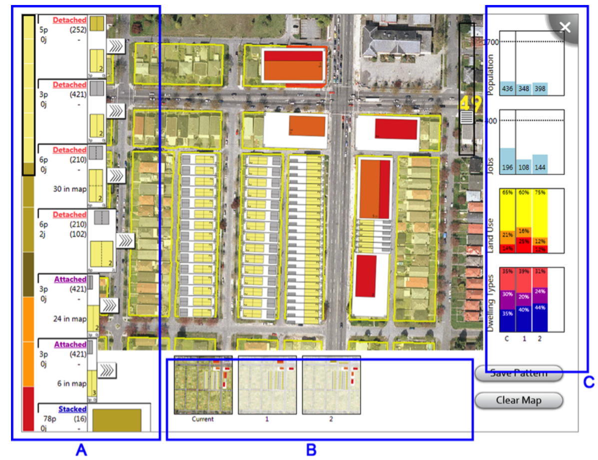

Figure 2. The first iteration of UD Co-Spaces, where the center of the tabletop is a map view of the *current pattern*, with (A) a *side bar* displaying a list of available cases that can be dragged onto the map, (B) a *bottom bar* showing a list of saved patterns, and (C) a comparison of the current and saved patterns based on a fixed set of indicators.

Understanding design consequences. Four summary charts provide quantitative visuals for key sustainability indicators in a reserved display area (Fig. 2C). These show target values (thresholds) so users can track how close they are to reaching their goals. Charts update automatically any time cases are added or removed. Users cannot interact with charts directly, they only make changes and then see how the charts respond. Previous patterns can be recalled from the *bottom bar* (Fig. 2B) that serves as a primitive history mechanism.

Challenges and lessons learned. The biggest problem with the initial prototype was limited screen real estate. Display size was not enough for robust design exercises. A lot of space was occupied by visualizations showing sustainability indicators that were considered too sophisticated for novice users. There was no 3D view in this version. The software was specific to a particular tabletop manufacturer. The background map had to be provided as an image file. The need to manually prepare maps put constraints on how much they could be scaled and thus limited the areas for which urban design could be explored using the prototype.

Iteration 2: Adding a wall display. We added an auxiliary wall display with a 3D aerial view and a custom-designed indicator dashboard (Fig. 3). Based on advice from domain experts, a simpler visual encoding using bar and donut charts (with simple infographics in the middle) to help users better understand the indicators was developed [24]. The natural up-down orientation of the 3D view and indicators was more appropriate for a vertical display. This freed up valuable real estate on the horizontal tabletop display, so it could be devoted to the 2D map and case bar for interaction (Fig. 4). 3D viewing parameters such as viewing angle, zoom level, and elevation were dynamically controlled using a custom widget on the tabletop.

Figure 3. The auxiliary wall display in the second iteration of UD Co-Spaces, with a 3D view (top) and new visual encodings for sustainability indicators (bottom).

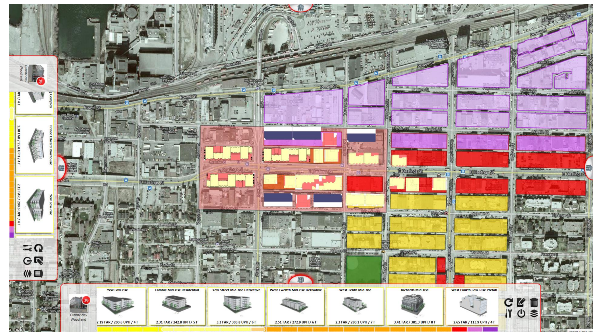

Figure 4. The touch-table interface in the second iteration of UD Co-Spaces, with a map of the study area in the center and a case bar along each edge of the display to allow individual exploration of options.

Revised architecture with federated services. UD Co-Spaces integrates three independent applications: a 2D map server to replace manually loaded map images, live access to a database where cases can be obtained, and a third-party renderer to display urban design patterns in 3D with cases at their correct locations. Dashboards were implemented so they update their views when callbacks notify them that the pattern on the tabletop has changed. To provide compatibility with future technology, the software uses a layered approach that introduces abstractions for the 2D and 3D displays and for the case database. *RabbitMQ* provides a bulletin-board-style messaging layer in which requests are broadcast and listeners associated with each federated component provide asynchronous responses. The federated architecture proved fortuitous when personal displays were added in the third iteration.

Device and service abstractions. Bindings were written to support SMART Technologies, Microsoft Surface, and PQ Labs multi-touch surfaces for the 2D tabletop (each device has about four times the area of the initial prototype), *Google Earth* for 3D rendering, *Google Map* and Microsoft *Bing* for 2D map content, and *elementsDB*, a database of cases developed previously by the researchers. Trimble's *Sketchup* was used to convert *elementsDB* case geometry into 2D images for the tabletop and 3D models that *Google Earth*'s API "inserts" at the appropriate locations and orientations for rendering by an *Apache* web server and display in a full-screen browser window on the wall.

Indicators. A new custom-designed dashboard provides visual encodings of key indicators that can have target values specified for "are we there yet?" interaction. These indicators can be used to determine near-optimal designs for a particular urban area.

Deployment. The second iteration was tested in a series of 26 workshop sessions with 44 citizens and planners in the British Columbia city of Revelstoke and 18 professionals in Vancouver. Sessions were video taped and data gathered through questionnaires and focus groups, yielding insights about the system design, collaborative interaction, engagement, and the value of immediate live feedback during the urban design process. We received positive responses from stakeholders that UD Co-Spaces was *fun*, *easy to understand and interact with*, *encouraging*, and *instructive* about the consequences of decisions: participants' feedback indicated that the system helped them see the impact of their designs, understand city planning and its complexity, and learn from each other. Those in the Revelstoke workshop remarked that the "tools were helpful in understanding some impacts of choices," "I learned a lot from [a developer] and [a planner] about how developers and planners think," it was "interesting to see everyone's views," "there are a lot of details to consider when doing urban planning!" and the process helped "understand city planning and its ramifications."

Features that both professionals and the public liked were *fast and early feedback*, *number and variety of alternatives*, and *visualization linked to the indicators*. The system was well received by professional planners, even though we had thought it would be mainly of interest only to non-experts. The Vancouver field trials involved six city planners and 12 other municipal staff in half-day design workshops. In follow-up interviews, they reported that seeing 2D and 3D concurrently with "live" indicators, enabled them to effectively engage with non-planner colleagues to generate and evaluate numerous alternatives. All of them reported that it raised their confidence about proposed solutions and they subsequently requested to use the tool set for additional work sessions.

Challenges and lessons learned. Analysis of videos, questionnaires and focus groups indicated some important limitations: lack of personal work spaces on the displays, difficulty interacting in parallel with the 3D view on the wall display, and low user engagement with sustainability indicators now that they were shown on the wall rather than at the center of attention on the tabletop. Adding indicators at the bottom of the wall display also created a display real estate problem: indicators took space on the wall that was supposed to be used for 3D. The set of indicators and target values were statically chosen; there was no opportunity to customise them for individual use. Some participants commented that the tabletop was so engaging that they did not pay much attention to the indicators on the wall. We addressed these issues in the third iteration of the system by adding personal hand-held devices to control the 3D view and for viewing indicators, thus freeing up the wall display for 3D while also encouraging more interaction with the sustainability indicators.

Figure 5. A dashboard on the iPad shows visual feedback about sustainability indicators for the current design. The left side is a toolbox of colour-coded indicator categories, the right side is a canvas showing the selected indicators. Users drag indicators from the toolbar to the canvas and can select target thresholds for each indicator.

Iteration 3: Adding personal hand-held displays. Our current version of UD Co-Spaces is an integrated multi-display environment (Fig. 1) whose activities are anchored in a multi-touch tabletop workspace augmented with both large-screen wall displays for shared viewing and smaller hand-held displays for individual access and customization. The federated use of services abstracted into layers and the message paradigm to support asynchronous communication continues. We improved interaction with the 3D wall display and added new functionality for interacting with indicators by introducing Apple iPad tablets that remotely manipulate the 3D view and configure and display personal indicator dashboards for parallel investigation of sustainability indicators. iPad applications use WiFi to communicate with the server that manages the tabletop and 3D display through agents resident on the server that respond to task-specific RabbitMQ messages.

iPad 3D view control. As in the second iteration, a direct manipulation multi-touch view controller on the tabletop initially sets the location of a virtual camera and its direction of view and elevation relative to a “look-at” point in the urban design. A new custom remote control iPad app then allows pan and scroll of the look-at point by one-finger movement, camera distance and orientation by two-finger pinch-expand and twist gestures, and camera elevation by two-finger virtual sliding. Our assumption that ubiquitous experience with personal computers, hand-held smart phones, and tablets has created a level of sophistication in the general public that implies that gestures such as zoom and pinch will be familiar to many people was definitely borne out in our testing.

iPad sustainability indicators. Dashboard indicators give visual feedback about sustainability indicators for the current design. Indicators can be grouped to display related information. A *dashboard* is a collection of indicators. Dashboards can be displayed on the tabletop or on the wall or on the iPads. On iPads, indicators can be dragged from a toolbox (Fig. 5) to build custom dashboards that display the indicators that matter most to users. We added a fixed bar on the top of the iPad using one-fifth of the display space to show default indicators that were most relevant to the design task. This was done for the lay people who were not necessarily familiar enough with the context of urban design to select the relevant indicators. The bar can be hidden if users need more space.

As in the second iteration, indicators are updated automatically whenever a change takes place on the tabletop, so they always show current data to everyone. Indicators are drawn from computational models in the *elementsDB* urban design database. To encourage more interactivity and transparency about how indicators are set, users can select target thresholds for indicators using the iPad. This also allows facilitators to interactively guide sessions if they want to explore a variety of scenarios with different thresholds.

Challenges and lessons learned. After deploying the third iteration we conducted formal and informal evaluations that we describe in the next section.

EVALUATION

UD Co-Spaces is intended to serve a large range of stakeholders. A primary concern is usability of UD Co-Spaces for different groups of stakeholders and to observe and analyze its effects on collaboration and engagement. All of our system design decisions and development processes were based on close collaboration with both academic and professional domain experts: urban planners in both Revelstoke and Vancouver, who used UD Co-Spaces in actual planning charrettes in the two cities, which served as field trials for our system.

An example of a low-level system design decision is when users control the 3D viewer from the tabletop. They need to hold a finger down on the table for 4 seconds to activate the 3D viewer camera controller. When using an iPad to control the 3D, they got confused about where the 3D camera is looking. We added an “eye” icon displayed at the center of the 2D tabletop to indicate that the camera for the 3D viewer is always looking at that point no matter how the viewing parameters change. When users let go of their fingers, the eye icon disappears automatically.

We also took the opportunity during a demo of our system to 28 high school students (two groups each of 14 girls) to test whether multiple users could smoothly use the iPads to control the 3D view. Each demo took 45 minutes. During the demos we provided 10 minutes of introduction, then we observed the students working freely with five iPads to control the 3D view on the wall display. Most of the students quickly learned how to perform rudimentary actions, confirming that (at least for younger stakeholders) almost-ubiquitous exposure to personal surface interaction can be assumed. In addition to this and many other informal evaluations that are part of normal iterative system design, we conducted two formal evaluations.

Heuristic Evaluation. A heuristic evaluation for both of the iPad applications was conducted with three experts in urban design and public engagement. We had one task for each application (3D viewer and indicator dashboard), and gave each expert 20 minutes to try each feature. After each task, an expert provided verbal comments about each application and provided us with suggestions to improve them. Each expert was tested separately for about 60 minutes. All three experts said hand-held devices were valuable. After comparing 3D navigation on the tabletop to navigation using iPad, Expert 1 stated that "iPad is easier to use for posture, it gives you better opportunity to find the 3D view, and it is more comfortable because of the posture (standing up and looking at the wall display on the wall)." Expert 2 said "controlling 3D is more intuitive on the iPad than controlling the 3D from the table" but that while he was comfortable with both "as facilitator [I] would be more comfortable on the table where everyone can see the interactions, but iPad is easier to get into than the table itself." Expert 1 said "gestures feel better on the iPad than the table, it takes some getting used to navigate on the table while looking up at the wall." Expert 3 made similar comments.

All three experts were also positive about how easy the indicators were to navigate and operate. Expert 1 mentioned "being able to modify the key/value pairs in the design task ... to react to people's interest is very important, being able to customise indicators for each group based on what they care [about] most is important." Similarly, Expert 2 liked "the ability to modify the indicators in accordance with the priorities of a group or a workshop." Expert 3 said "the combination of numbers and visuals [and] infographics is great" to visually encode indicators.

Formal user study. To evaluate the effect of UD Co-Spaces on engagement and collaboration, we conducted a user study comparing our current tool to the traditional paper map-based approach still widely in use. We recruited eight groups of 4-5 participants, most of whom were students at our university. Each group had a mix of people from different backgrounds. In each group there was at least one person who was familiar with urban design. Due to space limitations, we focus on results related to the use of UD Co-Spaces. Our qualitative results suggest that UD Co-Spaces promotes engagement, fosters collaboration, and helps users better learn about the consequences of their design choices compared to a traditional paper-based approach.

In general, UD Co-Spaces provided a highly collaborative environment for participants. Participants often worked in parallel, breaking off into smaller groups of 2-3 to discuss design issues and options. While the paper condition had a lower learning threshold, overall the interaction style of UD Co-Spaces was not a deterrent; participants quickly learned how to manipulate the table and the iPads. Our observations of many interactions with the wall display in UD Co-Spaces suggest that the 3D view is integral for engagement with the design process because it allows participants to see an approximate visualization of the neighbourhood as they design. We believe that UD Co-Spaces allowed participants to better understand how cases impacted the design by linking the information attached to each case to visual encodings of key sustainability indicators. Feedback from participants has corroborated the positive value of adding individual displays to engage people and allowing them to explore and customise data based on personal needs.

DISCUSSION

We adapted Arnstein's ladder and Snyder's principles to the narrower challenge of designing a CPSS targeted to the charrette process. Based on these principles, urban design experts' feedback, and our own observations of UD Co-Spaces in use, we synthesised a set of seven principles for urban design charrettes. We examine how UD Co-Spaces supports these principles using comments obtained from informants in our user studies.

1. Engagement. Based on our observations, we believe support systems for charrettes need to engage users on an individual and a group level in order to capitalize on the diversity of stakeholders. Engagement primarily refers to users engaging with one another, but it can also refer to how users engage with the system as well. Therefore, the system should act as a common space that engages participants with each other while also engaging individuals in the design task through innovative, and easy to use and learn features. Our study results show that using diverse displays, including the tabletop, the 3D wall display, and the hand-held devices, contributed to a highly engaging environment. Users interacted with various displays, which in turn resulted in increased interaction among the group members. As one participant stated, "The visual aspect of it is really engaging. You become kind of engrossed in it. I thought it worked really well in terms of getting people engaged in the actual process" (Revelstoke workshop). The collaborative tabletop was a space where multiple users could interact with the system simultaneously, allowing users to work individually or in groups, supporting engagement at both of these levels. Additionally, the 2D and 3D visualizations with familiar, easy-to-use interaction techniques made the system relatively easy to learn in a short amount of time, which makes engaging with the system more likely.

2. Collaboration. A main goal of design charrettes and our system is to foster collaboration through the co-creation of designs [7, 9]. In order to achieve this goal we deployed a multi-display, multi-user system that has a single solution space. Evaluation of previous iterations of our system indicated that the size of the design space mattered, and that limited space hampered collaboration by making the information difficult to access and manage. Subsequent iterations of the system included a large wall-display and hand-held devices in order to mitigate the issue of limited real estate. Indicators were moved from the wall display to the hand-held devices to save space, which had the added benefit of allowing individuals to customise the indicators they were most interested.

Tabletop. In line with previous research, we chose a tabletop to provide a collaborative platform to encourage collaboration [16, 20]. There are other collaborative PSS tools that achieve collaboration through the use of tabletops [10,13,17]. While we provided access to cases (building types) on each edge of the table to enable individual exploration, we deliberately provided only one shared space for the final solution in the middle of the table to encourage collaboration and co-creation of design.

Wall Display. Due to the spatial nature of urban forms, extra display space is needed to show the 3D view of a neighbourhood. Our studies, as well as other relevant studies, suggest that augmenting the tabletop collaborative platform with a vertical 3D view is beneficial. Therefore, we chose to display a 3D rendering of the design on the wall because the vertical nature of urban form suggests that wall displays would be more appropriate [10, 17]. Our observations suggest that the 3D view plays an important role in the design process.

Personal Displays. In the first iteration, indicators were shown on the table. Feedback indicated that the real estate on the tabletop was needed for interaction with the design. In the second iteration we moved the indicators to the bottom of the wall display to free up valuable real-estate on the tabletop. While professionals actively referenced the real time feedback of indicators, we observed that lay people did not interact much with the indicators. Indicators were far from reach, took up valuable space on the wall, and the choice of indicators was determined by the system. Therefore, we provided personal space through the addition of hand-held devices in the third iteration of UD Co-Spaces. This enabled individual exploration and customization of the indicators dashboard (indicators can still be displayed on the wall or the tabletop if desired). We received positive feedback about adding personal devices to improve interactions both with the wall and with the indicators. One participant said "I definitely really liked how everything was synced, specially with regards to the projection and the iPad and the table itself. Being able to rotate it so we could get a better view, and just being able to see everything unfold in real time" (Revelstoke workshop), which supports our decision to add hand-held devices to our system.

3. Interactive visualizations. The use of interactive visualizations in our system provided a number of benefits for participants, who represented diverse stakeholders in the design process. In line with previous research [1], our findings indicate that the interactive visualizations we provided helped foster participant engagement in the design process. Additionally, participants better understood the design process because they could visually see how their design decisions impacted sustainability issues through the use of indicators that changed in real-time as they explored designs iteratively. According to Salter and Campbell [19], "most true group interactions with the technology have been limited and remain somewhat reactive, rather than fully interactive." Despite our visualizations being little more than a dashboard, with limited interactivity, user study participant stated that "each interaction, including touch, move cases, [and then] drag, drop, and manipulate them will make a big difference" and he added that "the different representations including map, 3D, indicators, and back and forth between those adds a richness to participants' understanding." We observed a lot more attention being paid to the indicators in the third iteration.

There were at least 1-2 people in each group who interacted throughout the session with the indicators and communicated to the rest of the group how indicators were changing as cases were added or deleted from the design space. In each group, there were significant interactions with the wall display, with the 3D view providing important contextual information that helped participants make decisions about their designs. As one participant stated, "I think I like combination of all of them together because I could see all the information on one wall, I could see the 3D view on one, I could manipulate the view on the table, and I could see all the changes on the tablet. So for me it was the combination" (Revelstoke workshop).

4. Accessibility. In order to encourage participation of stakeholders with different backgrounds, expertise, and often different expectations, special attention is needed to make the system accessible and usable for different groups of users [9, 22]. Specifically, the system should be easy to learn and use, with effective and efficient work-spaces. It should provide numerous types of information including 2D maps, 3D views, examples of cases, and data visualizations, as well as numeric data to reach people with different learning styles.

To address users' needs, we observed charrette participants and their various concerns and objectives. A simple categorization of users in this context divides them into professionals and the public (or lay people). For professional planners, the ability to create and compare a diverse range of alternatives against indicators of performance is important. For public stakeholders the main considerations are increasing level of engagement, understanding the process, social learning, collaboration, and trust. Therefore, we used familiar visualization and interaction techniques and put a lot of effort to make access equitable by providing for individual exploration and input. We iteratively improved visualization and selected data representations for each display based on our evaluations. Our results suggest UD Co-Spaces might have a leveling effect on power and control. Based on observations during the formal user study, we noticed that the case bar allowed participants better access to and understanding of the information attached to each case, which impacted overall design choices made collaboratively. In addition, participants seemed more democratic in what they contributed to the design, whereas in the paper condition we noticed more "gatekeeper" roles emerge where one participant acted as a dominant voice, to the point of removing cases without any discussion or debate.

One participant in the user study said "We all subconsciously took on different roles in the project based on the areas that we felt more comfortable with ... [that] will definitely help in a real setting ... towards collaboration, ... we also learn from one another by being able to engage in real time with each other, with the knowledge that we brought to the table, and with the data that we were using" (Participant P13). Another said "Having this tabletop put every stakeholder involved so they can make changes themselves, see those changes right away, [which] promotes collaboration" (P15).

5. Iteration. It is well-known that iteration in design is a valuable exercise that can contribute to a better final design due to exploring many different alternatives [18, 27]. While using traditional paper-based methods limits the chances participants in a public workshop will explore lots of alternatives, digital tools provide opportunities to create and evaluate alternatives much faster. UD Co-Spaces supports multiple urban design iterations by providing fast and early feedback through

3D views and sustainability indicators. As one planning student noted, “Having the tabletop in terms of its usability and our ability to go back and revise and edit ... was superior to paper in that format. Instead going back and then erasing and then redrawing it out again, especially if you need to actually draw it out instead of arranging it by paper blocks. Definitely being able to edit on the fly and change on the fly helped a lot” (P13). This was apparent even in relatively short user study sessions. “We learned everything we needed to know from the software within the time period, but ... a longer workshop ... given different targets ... would just give more opportunity for more iterations of designs” (P11).

6. Understanding Consequences. One high-level goal of design charrettes is helping stakeholders understand and assess the consequences of their designs and therefore make more informed decisions. However, in conventional approaches this is a long and time-consuming process. Usually planners need to invite participants back for a second workshop session after the analysis and visualizations are ready when they all discuss the consequences and possible changes necessary.

UD Co-Spaces from the very first iteration included a visualization of indicators, although many users did not really understand the visualizations. In the second iteration we paid special attention to make them more accessible by different groups of users. Based on domain experts’ input, we used only donut charts with simple infographics in the middle and, when information was more appropriate for bar charts, we marked the target value on the bar as well as the current value to help see how close an urban design is to achieving its target value. These dashboards were added and tested during the deployments. While professionals really appreciated the new dashboards, lay people again did not use them much. The reason was different this time: one participant reported “the tabletop was so engaging that I did not look up to check the [indicators]” and another said “I looked up only to check the 3D but I did not really pay attention to the [indicators]” (Revelstoke workshop).

In the third iteration we enabled users to customise and get information about the indicators on iPads, which helped users improve their urban designs and understand the consequences of the designs. Multiple features were considered helpful in understanding consequences. “Having [indicators] and having that in real time definitely helped me understand ... the role that each decision was having both [in] terms of density [and] in terms of the lifestyle that was being lead to just through the indirect stats that we were getting. ... I definitely feel like that radically altered how we approached the project” and “the sync between all the devices [meant we were] able to make one change and then almost immediately see the impact that that change had both visually and statistically from the data ... the immediate interplay between the two” (P13). Similarly, each device brought a different understanding. “The iPad ... added an additional information source that gave me more context. [H]aving those different [indicators] that I could look at was really helpful to see, okay, what is the larger impact ... it was almost like stepping out and saying, okay, what did we actually do and what is the impact?” (P35).

7. Transparency. In order to engage the public in urban design, gaining trust is absolutely necessary [21]. “People are suspicious of ‘blackbox’ computer-generated answers. Models and assumptions should be as transparent as possible” [22]. UD Co-Spaces makes the process much more transparent by enabling users to customise indicators, set targets, and directly interact with them. We believe that this transparency creates better opportunity for understanding the indicators and trusting the outcome at the end.

“[Indicators] provide an orientation of what you’re trying to accomplish and making a connection to that. But, not to limit it just to those [indicators] is another consideration because you don’t want to go too far in one direction where you’re only considering active transit and commercial space because then you lose out on all the other [indicators]” (P36).

There were also misgivings. “I think [the indicators are] a bunch of data that isn’t necessarily useful to the public if it’s not translated ... the indicators seemed very arbitrary” (P25). This suggests that true transparency may require much deeper explanation of how indicators are calculated and what they mean. One expert who saw value in our design pointed out the possible irony that municipal planning departments might not welcome our system: “one caveat about all of this is that cities are reluctant to use this tool, because it is very open.”

CONCLUSION AND FUTURE WORK

We designed, developed, and iteratively improved UD Co-Spaces to engage the public in participatory urban design. Evaluations showed that it strongly impacted engagement by providing a collaborative platform where multiple users could interact with 2D, 3D, and indicator visualizations in real time. We assessed UD Co-Spaces using seven design principles for supporting design charrettes that offer guidance for developers of future systems. We suggest three areas for research.

Street view, overlays, and more. UD Co-Spaces currently lacks a street-view on the wall display, information overlay layers on the tabletop, detailed information about existing buildings in the planning area, and rich interactive control over indicators by facilitators.

More sophisticated interactive visualization. Visualizations in UD Co-Spaces are still very basic and need improvement. Cases could give previews of indicator changes using feed-forward techniques such as “scented widgets” [26].

History. UD Co-Spaces logs key iPad and tabletop events. A rudimentary *history browser* on the iPad can be used during or after a session to review the options that were explored. The log includes time of day, the tabletop group associated with an event (if multiple tabletops are in use), an optional event name, an extensible set of tags, and a snapshot of the design pattern at the time of the event. There are many questions still to explore, such as how to coordinate views when loading a pattern from the history to the table, how to interactively compare indicators across patterns, and how to best support browsing in the history. Our proof-of-concept history browser uses visual coding to identify events. We have not yet evaluated the coding. We suspect different history mechanisms are needed for facilitators and the public because they have different mental models of urban design.

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