Uplift: A Tangible and Immersive Tabletop System for Casual Collaborative Visual Analytics

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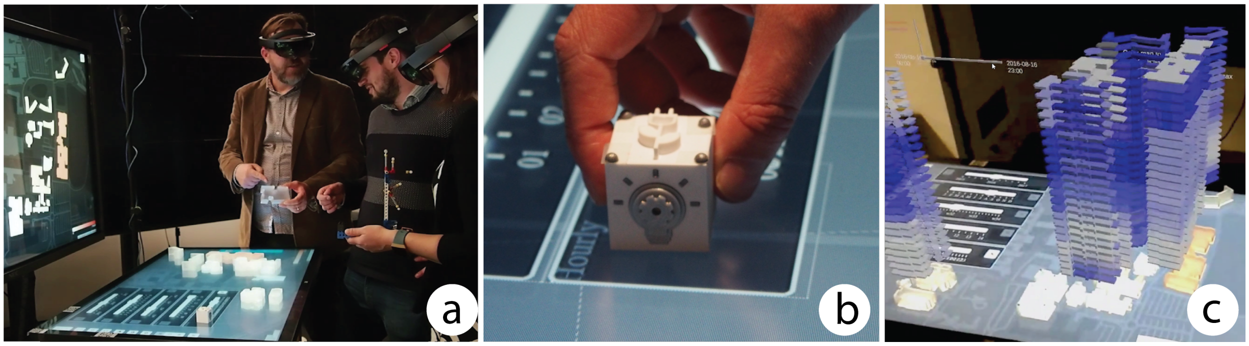

Fig. 1. Uplift is a novel system designed to support Casual Collaborate Visual Analytics. Co-designed with experts from a local smart grid installation, Uplift combines multiple technologies such as: (a) a central tabletop display to facilitate engaging discourse between knowledge-holders; (b) tangible widgets for intuitive and playful interaction; and (c) augmented reality for visualising data above and around the tabletop. This tangible widget (b) is used to select time granularity, which affects the number of time slices in a space-time cube visualisation (c)—in this case hourly changes in building energy consumption (greater colour saturation represents higher values)—which reveal various patterns in different campus buildings.

Abstract—Collaborative visual analytics leverages social interaction to support data exploration and sensemaking. These processes are typically imagined as formalised, extended activities, between groups of dedicated experts, requiring expertise with sophisticated data analysis tools. However, there are many professional domains that benefit from support for short 'bursts' of data exploration between a subset of stakeholders with a diverse breadth of knowledge. Such 'casual collaborative' scenarios will require engaging features to draw users' attention, with intuitive, 'walk-up and use' interfaces. This paper presents Uplift, a novel prototype system to support 'casual collaborative visual analytics' for a campus microgrid, co-designed with local stakeholders. An elicitation workshop with key members of the building management team revealed relevant knowledge is distributed among multiple experts in their team, each using bespoke analysis tools. Uplift combines an engaging 3D model on a central tabletop display with intuitive tangible interaction, as well as augmented-reality, mid-air data visualisation, in order to support casual collaborative visual analytics for this complex domain. Evaluations with expert stakeholders from the building management and energy domains were conducted during and following our prototype development and indicate that Uplift is successful as an engaging backdrop for casual collaboration. Experts see high potential in such a system to bring together diverse knowledge holders and reveal complex interactions between structural, operational, and financial aspects of their domain. Such systems have further potential in other domains that require collaborative discussion or demonstration of models, forecasts, or cost-benefit analyses to high-level stakeholders.

Index Terms—Data visualisation, tangible and embedded interaction, augmented reality, immersive analytics

1 Introduction

As sensing and computing power continually make new and exciting technologies accessible, data visualisation researchers strive to apply them in new ways to facilitate data understanding. In particular, much recent effort has been devoted to exploring how novel technologies such as multi-display environments [43], wall displays [42], tabletop displays [30], CAVEs [17], and augmented reality (AR) [8] can be applied to support collaborative data exploration, with experiences that reach beyond those available using desktop computers [46]. Because collaboration is a social activity, features are required for coordinating group activities [29], for instance to share data [26] or understand what others are doing [23].

These developments have led to the creation of sophisticated systems to support cooperative activity now known as collaborative visual analytics [25]. Powerful systems have been developed with the aim of solving complex problems with very large data sets in domains like biology [57] or intelligence analysis [53]. Thus, we tend to think of collaborative visual analytics as an activity reserved for groups of dedicated experts, using specialised tools for long periods in war-room like environments. However there are many instances, where engineers, project managers, network analysts and other everyday professionals deal with sufficiently complex problems to warrant collaborative analytics tools.

For instance, recent interest in smart grid technologies presents a highly complex domain involving many interrelated information layers, including physical infrastructure, network topology and loads, generation and storage, communication, and market dynamics [20].

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Moreover, a lack of experience with these new systems and technologies results in a lack of general understanding of how these systems will respond to choices in their deployment. To facilitate understanding in such a domain requires sharing of knowledge between a variety of stakeholders with diverse expertise. This activity should take place in an accessible everyday environment that encourages interactive exchange.

In this paper, we investigate an interaction paradigm we term Casual Collaborative Visual Analytics (CCVA), which combines ideas from multi-modal interactive visualisation techniques and collaborative visual analytics (see Section 2.3). Our design criteria (Section 3.7) aim to support everyday collaboration in short analytical sprints with low-barrier, walk-up-and-use technologies. Our formalisation of this concept emerged through the development of a novel prototype system, Uplift (Fig. 1). This system is aimed at supporting CCVA through the use of multiple emerging technologies: 1) a tabletop display provides a centerpiece for collaborative exploration and knowledge sharing; 2) a visually engaging 3D campus model to act as a physical referent [63] for geospatial and related temporal data; 3) tangible widgets to support playful and intuitive interaction [25]; and 4) augmented reality to allow use of interstitial space [55] above the tabletop [8] for compact visualisation of complex temporal data.

Uplift was developed in a co-design process with smart grid domain experts, which involved preliminary interviews, an elicitation workshop, and several feedback sessions with numerous participants with a breadth of expertise. Participants of our feedback sessions were enthusiastic about our developments and identified several use cases and scenarios where a system such as Uplift would be highly beneficial in understanding, knowledge-sharing, demonstration, education and decision-making. These sessions helped us to identify several successes in our developments and a number of opportunities for future work.

The contributions of this paper are:

1. An exploratory prototype implementation, Uplift, that combines a multi-touch tabletop display environment with AR and a physical reference model to support engaging embodied interaction with intuitive tangible widgets. Our implementation seeks to support Casual Collaborative Visual Analytics of smart-grid data both spatially and temporally.

2. Lessons learned from a thorough co-design process involving multiple stakeholders with expert knowledge in a real microgrid instantiation, that lead to insights toward future research.

2 Related Work

Tabletops have been widely used in information visualisation as they provide a large shared surface for the display of data, but also because they are well-suited to collaboration [30, 57]. After discussing related works that combine tabletop with either AR or tangibles, we focus on such support for collaboration in a visual analytics context.

2.1 Immersive Tabletops using AR

One of the main reasons researchers have combined tabletops with AR is to take advantage of the tabletop's interactive surface. Until recently, most AR systems only supported mid-air gesture input which is both tiring and inaccurate. The multi-touch surface of the tabletop provides more appropriate techniques to select 3D models [4] and manipulate them [24], as well as to perform more complex scene management like creating and manipulating complex 3D visualisations [8–10], and analysing CT scans [50]. On the other hand, AR has been used to complement tabletops by adding a third interactive dimension. Benko et al. proposed techniques to transition virtual objects from the 2D tabletop to 3D AR [5]. De Araùjo et al. presented techniques to extend 3D modelling on a tabletop with 3D visualisations in AR and mid-air gestures [18]. In a similar domain, Reipschläger and Dachselt used AR not only to provide a 3D view, but also for 2D complementary views and to visually offload 2D menus from the tabletop interface [45]. Finally, in collaborative contexts, AR has been used to provide a personal view to compliment the tabletop's shared view. For instance, AR can show different types of data depending on a users' expertise [12, 35], or for different points of view [34, 51, 52].

2.2 Tangible and Embodied Interaction for Visualisation

In parallel, researchers have also explored the embodiment of virtual objects using physical artefacts [19] called Tangible user interfaces (TUI) [21]. They have been found to be beneficial in particular in eyes-free [32] and visualisation tasks [14]. They can have an impact on memorisation, proprioception and user experience [54]. Underkoffler and Ishii explored the use of tangible buildings for urban planning on a projected tabletop [58]. Interviews with experts suggested that tangibles would facilitate prototyping, but also presentation to clients. A follow-up study by Ishii et al. showed that they also stimulate creativity and encourage collaboration [31]. Similar findings have been found in other application domains like genomics [40,49], and games [61]. Löchtefeld et al. showed that using TUIs also improved spatial memory [36], and Hull et al. showed how they can provide context to data visualisations [28]. When the tabletop is concurrently used with another display, tangibles can provide a convenient and intuitive link between the two views. For instance, Coppins et al. used tangibles on a tabletop to control the view of a camera displayed on a wall display [13]. Similarly, with BioNets [38], Manshaei et al. used tangibles to select and combine biological networks that are then displayed in a large wall displays.

Overall, the use of tangible controllers for information visualisation have been found to be beneficial. Ullmer et al. used tangible knobs to control parameters of visualisations. Frölich and Plate proposed the cubic mouse [22], a 3D mouse to explore 3D scans in Cave VR. Evaluations with experts showed it helped them perform complex tasks without any training. Similarly, Chakraborty presented CAPTIVE [11], a 3D cube to manipulate 3D models in AR. Also in AR, Bach et al. evaluate the use of a tangible controller to directly interact with 3D scatterplots [2], which showed better performance than with a desktop on highly interactive tasks. Cordeil et al. proposed using tangible axes with sliders for a similar task, which showed better performance compared to mid air gestures [14]. A design space for the use of tangibles in immersive visualisation is proposed by Cordeil et al. [15]. Even without tangibles, the use of embodied interaction has been studied in immersive visualisations via the use of direct manipulation of axis in the 3D space [3, 16], or of vibro-tactile feedback [44].

In the urban design domain, Alonso et al. [1] consider top projection of information onto a fixed tangible city model. Maquil et al. [39] also use top projection for urban planning, but instead of a fixed model use wood-blocks and other tokens as tangible affordances for interaction with buildings and other features.

2.3 Collaborative Visual Analytics on Tabletops

Heer and Agrawala provide a discussion of design considerations for collaborative visual analytics [25]. Their work seems largely inspired by online collaborative systems that were popular at the time, such as Many Eyes [60]. The style of collaboration considered was therefore largely asynchronous and remote rather than close in-person collaboration. Desktop computing environments are poor in this latter collocated case — small screen, mouse+keyboard devices are difficult to share — but emerging display and interaction technologies, from tabletop computing devices to AR, provide new opportunities for collaboration [6].

Researchers have created playful interactive visual interfaces for presenting data in playful ways. For example, Hinrichs et al. created casual visual interactive experiences primarily for libraries, museums and other public information displays, intended to complement the physical browsing of the venue [27]. Their systems were collaborative and engaging, but designed more for casual browsing by novice users to support their serendipitous discovery than to support analytics by experts.

Isenberg et al. present a table-based system for document analysis [30]. Close observation of pairs using the system found strong benefits from its support for closely-coupled work and communication. Participants were deeply engaged in a task for an extended period. While intended for deep analysis, the data was fairly homogenous (text) and interface provided little support for other (e.g. quantitative) data overlays. Similarly, Tobiasz et al. proposed Lark [57], a visual analytics system that encourgage mixed focus collaboration, which include phases where users work on their own, and phases with close collaboration.

A combination of table-top, wall and hand-held devices is demonstrated in the context of urban design by Mahyar et al. [37]. The scenario considered is highly relevant to the one we present in Section 3.7, using the personal hand-held displays to provide sustainability data dashboards, while the tabletop provides the collaborative surface and the wall display provides a 3D view. We further reflect on their design criteria when we introduce our own in Section 3.7.

It is our intention with this work to provide an interface that reflects the casual, somewhat playful, aspects of such past tabletop systems, but with a serious intention to support collaborative analytics between a variety of expert users and stakeholders.

3 Motivating Use Case: Communicating Complexity

To gain an overview of the complexity of the scenario and elicit data visualisation requirements we ran three interviews followed by a half day workshop with smart grid experts, including experts in global energy network systems and key stakeholders of the campus microgrid project (see Fig. 2). The Monash microgrid, as explained in Section 3.1, was in its early stages of development at the time of the elicitation phase and therefore many unknown factors were still to be decided.

3.1 Microgrid Context

A microgrid is a smart electricity network where supply and demand are effectively controlled and managed to optimise energy use with levels of generation and storage. As part of a commitment to reach net zero emissions by 2030, Monash University, the largest University in Australia, is building a state-of-the-art microgrid on the largest campus in Clayton, Victoria in the metropolitan region of Melbourne. The microgrid is providing a unique opportunity for researchers and practitioners to explore innovative solutions to today's energy industry challenges. These involve seeking to demonstrate the integration and orchestration of locally distributed energy resources, while optimising the use of generation and storage and maintaining network power quality and stability. This not only requires considerable technological exploration, but includes designing and testing new market incentives and different business models. There are many 'stakeholders' invested in the project from industry partners, academic researchers and building managers through to the staff and students using the campus everyday.

From our discussions with experts from the Monash microgrid we learned that their team consists of a diverse range of specialist, each using different bespoke software to analyse different data sources. We identified a need for a collaborative platform capable of engaging everyone together in discussions. We present some examples of the collaboration we envision in the following scenario:

Scenario

Sam is the project manager for a new campus microgrid. To support the considerable planning, engineering, and communication needed for this project, Sam has introduced a new collaborative tool. This tool presents a physical model of the campus tied to digital assets, which makes it possible to present campus information to multiple stakeholders in a simple and informative manner. In addition to providing an ***overview of complexity*** *in the microgrid, it provides* ***details on demand*** *intuitively; picking up a building reveals a detailed building view displayed in mid-air. Additional charts and other visualisations are situated in space above and around the tabletop, which are interlinked to show interconnections. This became a* ***focal point*** *in the project team's daily stand-up meetings. It is also used in the executive boardroom as a* ***demonstration tool*** *to demonstrate cost implications to investors, as well as* ***simulation and forecasting*** *of future scenarios. All of these uses help Sam* ***break down knowledge silos*** *in the team by enabling collaborative data-driven connections between members of several company departments and other stakeholders.*

While similar physical maps are commonly used, for instance in civic planning, the scenario shows how they can be combined interactively with digital assets to become engaging centrepieces. The use cases we highlighted – facilitating knowledge sharing, demonstration and education, and understanding complexity – were identified as promising applications for such a system designed to support the casual and accessible collaboration described. These outputs, presented later in Section 5.2, came from expert feedback on a prototype system implementation, Uplift, which resulted from a co-design process.

3.2 Research Method and Project Timeline

We apply a co-design approach to design and implement a preliminary prototype that aims to address the design criteria outlined above. 'Co-design' is a process that involves both experienced technology designers and domain experts working together on a problem [47], and has generative and evaluative phases [48].

The co-design approach was initiated with an elicitation workshop with a combination of visualisation designers and domain experts. A multiple stakeholder co-design workshop was seen to be necessary after our initial interviews with energy systems experts. This elicitation phase, forms the generative phase of the design process, provided a number of relevant problems in the target domain, their associated priorities and use cases as well as helped us to define the design criteria described in Section 3.7. The evaluative phase initiated after the first development iteration, where feedback sessions demoing a working prototype were held with two different groups of domain experts (see Fig. 2), in order to understand similarities or differences in potential use with both groups of experts as well as understand further design requirements. Figure 2 provides an overview of the project phases that took place over a 12 month period.

3.3 Interview Procedure and Participants

To understand the potential for microgrid data visualisation two of the authors undertook semi-structured interviews with three energy network systems experts, who had also been involved in significant research into the proposal and feasibility reports for the Monash microgrid. These interviews involved open discussions about the scope and potential for visualising microgrid data. One of the three participants maintained involvement in the project during the later stages of the feedback process (see Fig. 2).

3.4 Interview Results

The results of the interviews identified that there were many potential users for visualising the data of the microgrid. Uses include network planning, maintenance, real-time operations and market analysis (see Fig. 2). Discussions about visualisation tools identified that a single system could be developed to be flexible and adaptable to the needs of multiple users, perhaps a system that allowed new data sets to be integrated as they became available.

One topic discussed was visualisation for real-time monitoring of the microgrid *'control rooms usually look like nothing is going on'* i.e. things function normally most of the time, but there are *'important critical moments that arise which operators need to be prepared for'*. Visualising the location and priority of alarms (to detect problems) for instance was seen as beneficial for operators.

Discussions also touched on the need to understand the monetary value of the microgrid resources, as well as the need to understand and compare the thermal performance of the different buildings. Flow and load of grid components was described as useful for planning, with historical data and forecasts being essential for understanding what was planned verses what actually happened. This was noted to be like *'crime scene reconstruction'*, where we can recreate the conditions that led to a failure and solve the cause. For parametric models we can *'tweak levers to adjust settings and see outcomes'*. Uncertainty in models was also noted to be important, but can be difficult to explain.

These interviews helped to inform our understanding of the scope and complexity of the microgrid domain. They also identified the wide scope of personnel that were involved in the Monash microgrid initiative and the need for the communication of data at multiple levels,

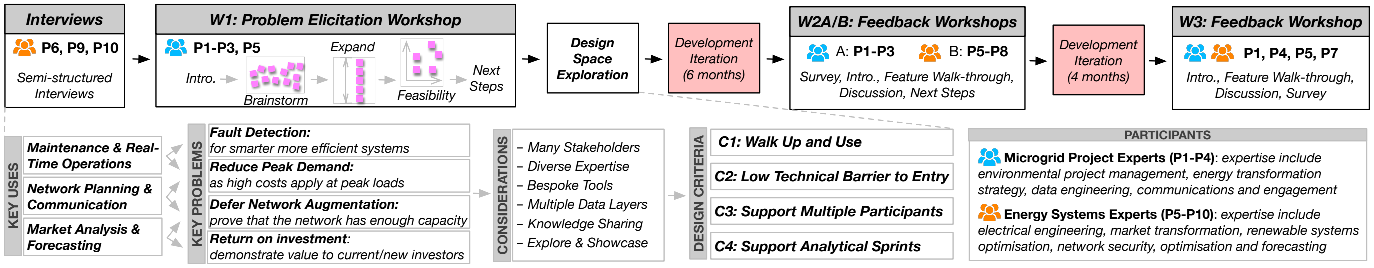

Fig. 2. Uplift co-design timeline, methods and participants, with identified key uses, problems, considerations and resulting design criteria

and the complexity of interplay between them. The outcomes of the interviews led to our decision to run an elicitation workshop with key stakeholders of the microgrid program, to gain a deeper understanding of the current needs and whether visualisation can play a key role.

3.5 Workshop Procedure and Participants

A half day requirements workshop was facilitated by two of the authors. Participants included a mixture of four Monash professional staff members with key roles in the microgrid and net zero initiatives (see Fig. 2), together with three data visualisation academics (ranging from Professor to Research Fellow) who had limited knowledge of the microgrid initiative. Their involvement was to help steer the open discussions and ideas towards data visualisation needs and tasks. The domain experts maintained involvement at various stages of the co-design process (see Fig. 2). The visualisation academics are amongst the authors and maintained their involvement throughout the process.

Workshop activities were developed based on our previous work [33] to extract domain knowledge from the experts, to promote collective brainstorming of the key problems and to identify possible areas where visualisation can be beneficial. After introductions, a short presentation about goals of the workshop and the goals of the microgrid for the non-domain experts, we ran three specifically planned activities.

The first activity sought to gather a wide and open selection of *key problems* associated with the microgrid. The second activity expanded these problems in greater depth, asking the participants to choose a key problem that they wanted to discuss in a group. Seeking to define: *what* the problem was, *why* this was a key problem, *why else* it was relevant, *how* it could be resolved and *how else* it can be tackled. Many ideas were generated. This was to help us understand the domain problems, the similarities and overlaps of those identified in activity 1, and the reason why each of these problems needing to be resolved. Finally the third activity involved a feasibility matrix of the items that had been discussed during the previous activities. Participants placed items in order of prioritisation based on two axes: *low-high priority* (i.e. business need) verses *easy-difficult implementation* (i.e. expected difficulty). This provided a wide picture of possibilities verses prioritises as well as identify possible quick wins.

The workshop was held in an open bright meeting space, with refreshments and the facilitators encouraged open discussions on the topic. Along with post-it notes and butcher paper, a 2D map of the Clayton campus and a 3D printed map of a different Monash campus (borrowed from a previous unrelated project) were on the table to prompt and encourage discussion about the campus and how information could be visualised.

3.6 Workshop Results

In the first activity a wide selection of key problems were identified. This included a need to better understand each *'building's use'*, *'how much energy we are producing and how much we are using'* and *'building demographics'*; knowing *'when, how, why'* energy is used; being able to do *'real-time monitoring'* of the microgrid and *'anomaly detection'*; understand the *'reliability of the data'* and the *'forecasts'*.

Participants emphasised the need to see several 'layers' of data from *'business, technology, control and power grid'*. Such a multi-faceted view is necessary to see complexities such as *'electrical flows at the same time as the market data'*, which would enable their team to *'tell data stories'*, *'plan scenarios'*, *'shift loads'* and ultimately *'change the market demand'* to *'reduce emissions'*. The participants identified the need to *'share knowledge'*, *'inspire others'* and be able to *'collaborate'* in the data analysis, although it was noted that this was really difficult to do at present with different knowledge sets, different software expertise and data in many different locations.

Identifying Topics – In the second activity the participants chose to further explore four large problems that they want to see resolved (see Fig. 2). These were wide and diverse topics that sparked substantial discussion that helped identify a need for a flexible visualisation tool that includes the many 'layers' of the microgrid data, each with very different anticipated users.

By delving into the *why* and *how* for each problem, the participants highlighted some key data visualisation tasks and insights, including the need to help *'see the micro and macro'*, *'find missing data'* ,*'identify peak load hits'* , *'identify suspicious patterns'*, *'identify failing meters'*, *'forecast renewable generation'* and *'real time reporting'*. . For real-time operations, the discussions identified that visualisation can help to *'avoid damage'*, *'improve reliability'*, *'allow proactive maintenance'*, *'detect anomalies'*, and *'understand fault causes'*. Whereas, visualisation through *'connecting layers'*, *'story-telling'* and a *'timeline of progress'* were identified as solutions for the need to *'simplify the complexity'*, *'convince stakeholders'* and *'remove barriers'*.

Visualisation Goals – The final activity identified problems that can be defined as 'high impact and easy to implement' . Such problems include the need to *'show when the peak demand occurs'* and identify *'the source of the demand'*, as well as to *'tell the story of the peak demand'* and *'tell the story of the return of investment'*. This could involve presenting the building meter data for electricity consumption together with generation and storage capacity over certain periods of time. *'Visualising the forecast of the network'* was seen as moderately important and moderately easy at this stage, with *'real-time analysis for operators'* being highly important but difficult to do at present. The question of *'how can we reduce peak demand?'* together with the action of *'reducing the demand on the grid'* were seen as key goals for the microgrid project, but too difficult to tackle at this early stage.

Tangible Props – Discussions in the workshop mostly took place around the butchers paper, which were hanging on the meeting space walls. The participants as well as facilitators wrote on post-it notes and these were placed on the paper. Yet, we noticed that the 3D model of the campus became a focal point for discussions about the buildings and the campus. Participants pointed at the models and acted out ideas with their hands drawing invisible connections between the buildings. Despite the 3D model representing a different campus, it was noticeably more useful as a prop for these discussions than the 2D map of the relevant Clayton campus laid next to it, which was never used. We had brought the model and map to represent the campuses, yet the fact that the model had such a key influence on participant's actions during the discussion was a really interesting observation. This difference may simply have been because the model was larger in size (slightly larger than A3 in size compared to the A3 map), or because the buildings announced to be in the first phase of the microgrid were still to be determined, but it seemed that the 3D model provided a useful tangible interface to help describe the connection between the buildings and present the invisible data. We took this observation along with the insights and ideas through to our design process.

3.7 Design Criteria

Based on the use-case and co-design process explored above, we identified several characteristic design criteria required by systems to support CCVA:

C1 Walk Up and Use – as a collaborative centrepiece, the system should be intriguing and compelling. It should be inviting to any users, including those who are presented with it for the first time.

C2 Low Technical Barrier to Entry – the tool should present minimal barriers to users with varying degrees of technical knowledge. Information presented by the system should be easy to interpret, and interactions should be discoverable and intuitive.

C3 Support Multiple Participants – the system should be flexible in terms of number of users, from small groups of 2 or 3 to larger groups. A company may want to bring together different groups at different times, for instance knowledge holders from different areas of the company, executives, or visiting clients.

C4 Support Analytical Sprints – the system should support short bursts of analytical activity from 5-20 minutes. This may be part of other activities such as a workshop, conference meeting or spontaneous activities. For this, the system needs to establish a shared common ground [25] for collaborators, including a shared state space and the ability to understand others' interactions.

C1 and C2 in particular, echo the call of Mahyar et al. [37] for, respectively, *engaging* and *accessible* urban planning systems. C3 also echoes their call for *collaborative* systems, but our focus on supporting different types of experts (C3) working in short bursts (C4) brings a different analytical focus.

Although developed during co-design with experts in the smart grid domain targeted in this project, we intend these goals to be domain-agnostic and applicable to a wider breadth of potential systems. Our prototype system, Uplift, described in Section 4 aims to address these four key design goals.

4 Uplift Prototype System

Based on our initial interviews and elicitation workshops, we developed a prototype system aimed at collaboration between users of the microgrid and facilitating data exploration and sharing knowledge from its many 'layers'.

4.1 System Overview

The Uplift system consists of four integrated components (Fig. 3), allowing users to explore complex data and exchange knowledge in an collaborative and intuitive way, reflecting each of four CCVA design criteria **(C1-C4)**:

Tabletop Display – A tabletop display shows a geographical map and provides a platform to place interactive widgets (Fig. 1a,b). This centrepiece **(C1)** supports common understanding with the shared model, and natural collaborative cues **(C3)** such as gaze to indicate collaborator's attention focus, deictic pointing gestures, and placement of tangible objects [25].

Tangible Widgets – Tangible widgets are used as an engaging, intuitive, and playful way to interact with the system **(C2)**. The building model provides a physical referent for embedded data visualisation [63] and physical interaction controls provide an intuitive means for collaborators to share in customising the visualised data and layers **(C4)**.

Augmented Reality – Headworn AR displays allows data **(C4)** to be displayed in interstitial space above and around the tabletop [55]. This AR view provides a visually stimulating way **C2** to visualise multiple data types in a compact space by using 3D visualisations above the physical model, as well as multiple standard 2D visualisations in

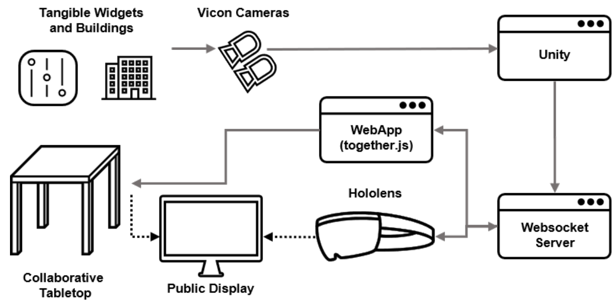

Fig. 3. System diagram showing components and relationships

the surrounding space . AR headsets also provide the advantage of providing either private views for individual analysis, or public views sharing collaboratively.

Large Display Backdrop – We included a large display screen, situated adjacent to the tabletop **(C1)**. Unlike many multidisplay environments where such a large display serves as a focal point, the display in this case is intended to serve as a peripheral display space, for instance to place additional standard 2D visualisations. A large display situated above the tabletop height also has the benefit of being visible to larger groups **(C3)**, which can serve purposes such as replicating the contents of the tabletop, or sharing the AR view of a demonstrator without the need for others wear an AR headset **(C2)**.

4.2 System Implementation

The 46 inch tabletop display shows a web application that uses D3 [7], Leaflet [1] and Mapbox [2] to implement the visual interface. We use Microsoft HoloLens devices as AR displays, with Vuforia [3] tracking for calibrating the tabletop position. Tracking of the tangible widgets is performed using a Vicon [4] tracking system and a Unity application. The individual components are communicating via Mozilla TogetherJS [5] . This provides a simple service for adding collaborative features to web applications. The service uses standardised websockets for communicating between different instances which we facilitate to connect the different components of the system.

Tangible Widgets Controller – This application runs in conjunction with a Vicon tracking system, in our case consisting of four Bonita cameras and the proprietary Tracker software. In Unity we created a 1:1 scale virtual avatar of the tabletop dimensions, and map the orientation and position data sent from Tracker onto our virtual objects in the scene. In the case of the tangible buildings, the positions and orientations of these are forwarded as JSON strings to the HoloLens via the websocket server. The time granularity widget exists as a physics RigidBody within unity, and controls the date granularity by entering trigger collider zones - scaled to match the UI element dimensions of the tabletop app - and sending the collider's associated time property upon the trigger entry event. The slider widget consists two objects within Vicon Tracker and Unity: the base and the movable slider. The distance between these two represents the slider value sent, and the orientation sets the visualisation mode.

HoloLens Application – The HoloLens application was built in Unity, as a Universal Windows Platform application, and uses three Vuforia fiducial markers laid on one corner of the tabletop to correctly align the view in real world space. The HoloLens connects to the websocket server, and assigns itself a unique ID of a random number within a range of a 32 bit integer, in order to allow for multiple hololens users. An event handler listens for messages on the Websocket server, and reads the JSON strings for date granularity, visualisation mode, selected

[1]https://leafletjs.com/
[2]https://www.mapbox.com/
[3]https://www.ptc.com/en/products/augmented-reality/vuforia/
[4]https://www.vicon.com/
[5]https://togetherjs.com/

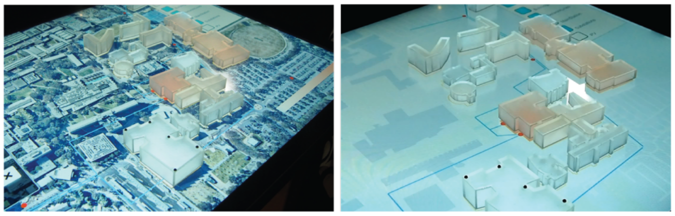

Fig. 4. Users can select from multiple background views: satellite (left) and map with the electrical network of the campus (right)

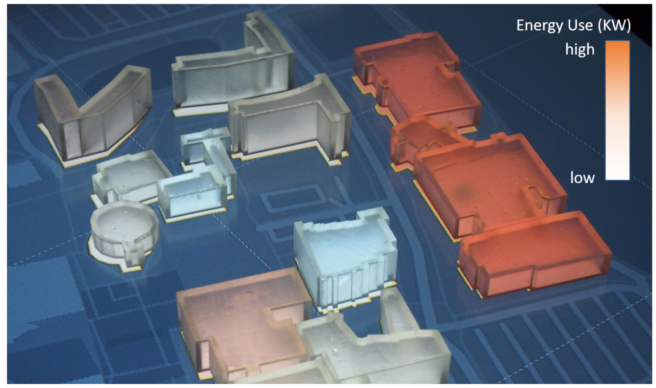

Fig. 5. A scale campus model provides a referent for embedded visualisation. Here energy consumption is shown by colour saturation.

building ID, selected building position and rotation, and slider values, in order to control the locally parsed CSV data driven visualisations.

4.2.1 Prototype Data

Data for the prototype was collected in collaboration with the microgrid project experts (Figure 2). This included electricity consumption for 18 buildings, that had been identified as being part of the first phase of the microgrid. This was provided at 15-30 minute intervals, depending on the building metre. Due to rollout of the microgrid, live data was not yet available for all buildings, so for more complete data we were provided historical data for the period of mid 2015 to early 2017 to prototype the system. We aggregated this data to hours, days, weeks, months and years, as these were expressed as useful periods, where patterns in electricity usage can usually be seen. Due to the fact that the solar installations were brand new, we chose to use the current installation locations and their maximum capacity to simulate what the generation would have been at the historical time interval. This was based on historical solar exposure records available from the Australian Bureau of Meteorology [6] . For the map layers we used existing building footprints from OpenStreetMap (OSM) [7] . In addition the electricity network, stations, new buildings, photovoltaic (PV) and battery locations had recently been digitised for another project based on campus maps, microgrid plans and recent aerial photography from Nearmap [8] as ground truth.

4.2.2 Campus Scale Model

The tabletop holds a scale model of the campus buildings that are involved in the current phase of the microgrid project. The model is composed of tangible building widgets, each the shape of its respective real-world building, but with surface details abstracted for simplicity. Heights were scaled by a factor of three in order to facilitate easier manipulation by users. The 3D mesh was generated by using OSM, and Blender, using building vectors and height data. The models were 3D printed using a clear SLA resin to make them translucent. This allows the energy consumption colour shown by the buildings layer on the tabletop display to shine through (see 4.3.1, below). Moreover, buildings can be picked up, triggering additional details to be shown in space around the building using AR (see 4.3.2, below).

4.3 Uplift's Visualisation and Interaction Features

4.3.1 Data Encodings

Uplift provides multiple features for visualisation of spatial, temporal, and other data related to the campus microgrid.

Tabletop Surface Visualisation – Uplift supports three different base maps. In addition to a satellite map (using an Nearmap API for up-to-date aerial maps), we integrated two simplified abstract maps (created with Mapbox Studio), one suited for bright and one for dark environments. The advantage of the abstract maps are that they allow the user to focus on the building and microgrid infrastructure and not be distracted by the geographical satellite details.

[6]http://www.bom.gov.au/climate/data-services/solar-information.shtml

[7]https://www.openstreetmap.org/

[8]https://www.nearmap.com/au/en

On top of this base map, users have the option to select three different layers that can be toggled individually. Each layer shows a different aspect of the microgrid and addresses a different user task. The PV layer shows the locations and sizes of all the PV panels that are generating energy in the microgrid. The station layer shows the locations of main and sub-power stations in the microgrid. The network lines layer shows the power network lines connecting these components.

Embedded Data Visualisation – To visualise building energy consumption, we use embedded visualisation [63] by encoding the relative energy used by each building as a colour displayed directly on the building surface (Figure 5). A colour representing the building energy consumption is displayed on the buildings layer of the tabletop display, however, due to the transparent building material, it looks at though the whole building is coloured as shown in Figure 5. We use a linear colour range from zero to the maximal value in the current range, which changes based on the particular instant and time granularity selected by users, as is explained in the next section.

Situated Data Visualisations – Uplift's use of AR allows other data visualisations to be spatially situated in space above and around the tabletop. Fig. 6 shows how solar energy generation and weather data are visualised. Solar generation is encoded by a set 3D bars (Fig. 6-right); each bar is situated at the location of its respective photovoltaic cell array, with the generation at a given time represented by the bar's height. An interstitial 2D view (Fig. 6-left) is used to display a traditional line chart showing temporal weather data, such as overall solar exposure and daily temperature range.

As an alternative to the embedded visualisation building energy consumption, users have the option to view a temporal overview of a given time frame through a space-time cube visualisation (Fig. 1c). In this view, energy data visualisations are situated in the space directly above each respective building, with time represented by the vertical axis. Several 'slices' appear above each building representing time increments, with higher slices showing later times. The number of slices depends on the time granularity (e.g. 12 month slices) selected by users, as discussed in the following section.

4.3.2 Tangible controls

In Uplift we use three different type of widgets: buildings, time granularity picker, and time slider. Together, these widgets support a variety of novel interactions, as follows.

Drilling Down in Time – The time granularity picker (Fig. 7) is used to select the time granularity of the temporal data visualisations. The selection is controlled by moving the tangible widget between several slider regions (yearly, monthly, weekly, daily and hourly) on the tabletop display (Fig. 1b). By default the yearly view is selected, which allows selection of a specific year. Users can move the time widget down to allow selection of a single month within the selected year, and so on, down to the granularity of hours within a selected day.

Sliding Through Time – The time slider (Fig. 7) allows users

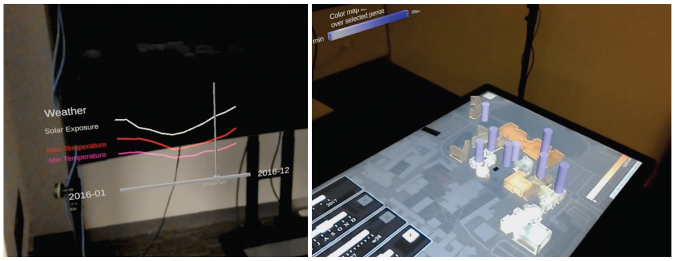

Fig. 6. Left: An interstitial view behind the tabletop shows a standard 2D line chart of solar generation over time. Right: Energy produced by photovoltaic cells on campus building rooftops is visualised using 3D bars placed directly on top of the tangible buildings, with an legend visible in space behind the table.

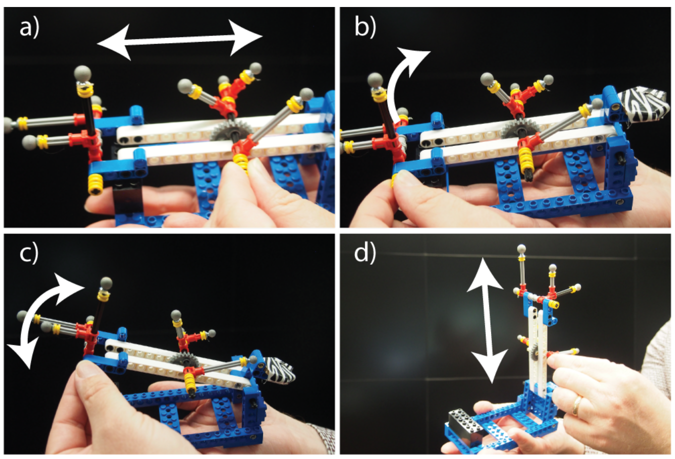

Fig. 7. Time slider. (a) When down, slider motion animates the time-series visualisations. (b-c) Lifting the slider activates the space-time cube mode, (d) in which slider motion controls the highlight plane.

to navigate within the chosen date granularity. For example, when the time picker is in the monthly view regions, the time slider can be moved through each month, to select a specific month for closer inspection. 'Scrubbing' through the consecutive months causes an animation of the times series visualisation, for instance showing how energy consumption or solar generation changes during a given year.

'Lifting' Time Above the Tabletop – The time slider contains a hinge that acts as a mode switch – when a user lifts the slider to its vertical position, the space-time cube visualisation appears above the buildings (Fig. 1c). By default all of the time slices are opaque. When the time slider is moved up or down along its axis, a highlight plane [44] appears, which highlights one opaque slice, with the remaining slices now semi-transparent.

Whereas the animated time visualisation is useful for viewing a sequence of events, the space-time cube allows an entire time frame to be seen in a single overview. This visualisation technique is typically used to show movement of objects, however, in Uplift it is aimed at allowing users to compare temporal changes between different buildings. To compliment the animated view, which uses a single colour scale for all buildings, the space-time view uses individual scales, allowing peaks and troughs to be seen within each building.

Inspecting Buildings more Closely – Uplift takes advantage of the natural affordance of building widgets by allowing users to pick them up to view a detailed virtual building model through the AR display (Fig. 8). The virtual model is overlaid on the physical one and can be manipulate in 6DoF. Surrounding the building, users can see supplementary data about its floor-space allocation and the amount of energy consumed by different systems within the building.

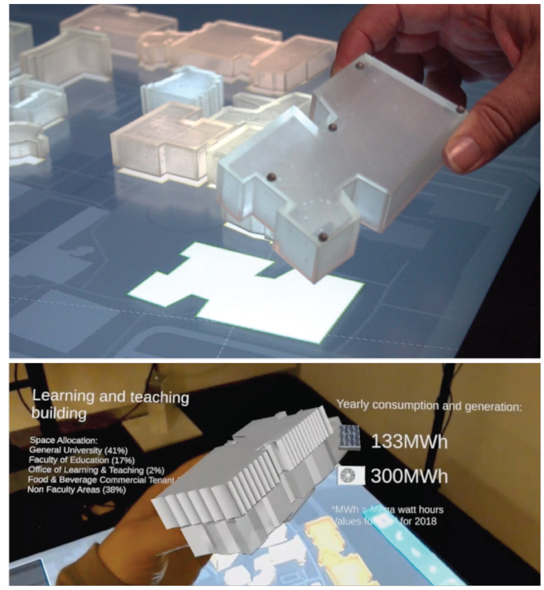

Fig. 8. Tangible buildings are tracked in space. When a user picked one (top), a more detailed 3D model overlays the real building and additional data are displayed (bottom).

5 Expert Feedback Sessions

As part of our co-design process, we conducted feedback sessions both to provide formative feedback on our developments and to help us evaluate our prototype system (W2A-B & W3 in Fig. 2). Initial feedback was collected at two stages during the prototype development. The first instance occurred after the initial system features were implemented and involved two sessions with varying expertise. A third feedback session was held at the end of our development. These sessions helped to guide our implementation, to identify features requiring for improvement or further exploration in future work, and provided valuable feedback to determine how well the system met the proposed design criteria (Section 3.7) and to identify useful application areas.

5.1 Procedure and Participants

Two initial feedback sessions were conducted to gain varied perspectives. The first session was held with the key stakeholders of the campus microgrid project, the second with more energy network systems specialists (see Fig. 2 for details for W2A-B). The final feedback session (W3) contained a mix of members from both groups to provide a more holistic overview.

Prior to each session, new participants were invited to complete a short survey of 6 questions using Likert scales from 1-5 to gain an understanding of their knowledge and familiarity with the technology. This involved: 1) knowledge (novice - expert) of the Monash microgrid; their familiarity (not all familiar - very familiar) of 2) with AR and 3) tabletop devices; and their use (never - everyday) of 4) tabletops, 5) tangible objects or 6) AR for data exploration. 6 of the 8 participants completed the survey. All 6 claimed a very high-expert knowledge of the Monash Microgrid. Most had a low to moderate familiarity with AR and lower familiarity with tabletop devices, with 4 not at all familiar. Of the 6, 3 had never used AR for data exploration, whilst 1 participant had good familiarity. None of the 6 had previously used tangible objects or tabletops for data exploration.

In each session we invited participants into a room containing the system prototype to demonstrate its full functionality. We began with a walk-through of the current system features, starting with the simpler tabletop functionality and then moving to features involving tangible widgets and AR views that required users to wear the AR headsets. The AR features were first demonstrated by one of the session invigilators wearing a HoloLens, whose view was shared on the system's large display. Following the demonstration of each feature, participants were invited to experiment with the interface as a group. For viewing the AR features, we had three HoloLens headsets on hand so multiple participants could try them out simultaneously.

We captured audio and video recordings of participant feedback during each session, and transcribed these for later analysis. Each of the 3 sessions lasted roughly 1 hour. At the end of the final feedback session, participants completed a Van der Laan acceptance questionnaire, which assesses user acceptance with 9 questions along 2 dimensions: usefulness, and satisfaction [59].

5.2 Promising Applications for Uplift

In our analysis, we identified several potential instances where systems such as Uplift could provide practical benefits.

5.2.1 Sharing Knowledge

Participants confirmed the intentions we came away with from our initial elicitation workshop, that a system such as Uplift would be useful for helping users to share knowledge between users with different backgrounds and knowledge sets **(C1-C4)**. For instance P1 commented, *'I think that collaboration piece in terms of trying to figure out a problem, or something along those lines – I think that's a useful exercise. I imagine there could be an operator in the room, and then one of the building occupants, and then maybe one of the guys dealing with the plant trying to figure out why was your energy bill so high?'*

One exemplary instance occurred during our first feedback session, when P2 was able to easily identify a particularly high peak in energy consumption shown in the tabletop visualisation: *'actually it's the lights. The lights on the hockey field, in winter.'* P5 later recollected this instance, remarking *'it's like you saw the value of [P2] knowing the reason why... there was because of the lights that went on.'*

5.2.2 Data Storytelling: Demonstration and Education

Participants recognised the potential of Uplift for communicating with energy users **(C3)**. For instance, P5 explained how a visually engaging system like Uplift could be used for *'demonstration purposes, showing people how... that's the first thing, it's that education awareness, and they don't want to look at spreadsheets of data, or charts.'* P2 commented how showing grid infrastructure data on the tabletop's spatial model *'makes it a lot more accessible to people who aren't electrical engineers'* **(C2)**.

P2 later offered a general scenario of how the system could be used to visually tell a story: *'Here's an example of where we lost power in this building, and this is what led up to that kind of thing.'* However, P5 noted that although the system could provide a *'good narrative and story,'* the physical model has limitations, since *'From a energy operator's point of view, they usually would want to see – to be able to zoom in and see a bit more.'*

Participant feedback also suggested that a system like Uplift could be used to help educate energy users about the impact of new smart grid technology on their operations. For instance, P1 explained *'That's something the customers are really interested in because those different zones within a building represent their staff and their operations and areas that might have sensitivity to us controlling temperature.'*

5.2.3 Overview for Understanding Complexity

Participants discussed how a particular challenge of smart grid systems is a general lack of experience and knowledge about their complexity. For instance, regarding a current installation of a large battery, P2 explained *'no one across the industry will know how this battery is going to respond in situ. So understanding its data for when it's charging and discharging, and then being able to see the data of the solar generation, and then the consumption of the building and those sorts of things – looking for that correlation to be useful, because there's a way to match those data sets. P5 brought us a similar complexity in the effects of wind on building climate systems: , the flow of wind does affect the cooling significantly – the heating and cooling rate of the buildings. But it also affects the macro level, how different systems mix their energy.'*

P2 explained how our system could prove useful in presenting a concise overview of complex systems, for instance by showing an intuitive view of solar exposure: *'I think it's better if you've got all the different pieces in the same view... rather than having to jump through different desktop views to get all that information, it's all there in one go!'* **(C2)**.

By encapsulating data from these complex systems in a single visualisation tool. P5 mentioned *'So it'd be really useful, real quick way of going – right, so lets take year worth of data from last or five years worth a data... and let's have a look at what's going on – and very quickly, without having to go through lots of spreadsheet analysis, very quickly visualise some of the key patterns'* **(C4)**. P1 similarly commented on the potential usefulness of presenting a high level overview to network operators, *'Let me say this, the fact that you can bring up like networks and assets like that – I'm just thinking of another audience for this... network distribution network operators to actually take a look at their assets, because their challenge is trying to manage peak demand across a whole system'* **(C2, C3)**.

P2 commented on the tangible interaction in Uplift allows users to easily explore different time frames, beginning from a high level: *'to be able to drill down... to your months, to your weeks, to your days – if you're starting from a high level, that would be the way that you'd do it – and generally the scale that you're given another tools is like you have to pick a date range. And you have to pick this date at this particular time to this day at this particular time. It's really annoying that you have to do that every single time you want to change it'* **(C4)**.

5.3 Feedback on Uplift Implementation

Here we discuss several topics related to the system's features and implementation that we consolidated from the three feedback sessions.

5.3.1 Engagement of Tangible and AR Features

Participants liked the tangibility of the interface **(C1, C2)**. For instance, P1 commented that the physical model *'gives an extra feel for scale'*. Participants particularly liked the concept of viewing information about a building when it's picked up. Despite our implementation revealing only basic statistics about a single building, P1 commented *'the fact that you can pick this up and say "this building" – there's not much to it, but it does something!'*. P5 further commented that this feature would be useful for communicating concepts to energy users **(C3, C4)**: *'if users could just pick up a building and it showed you: currently the Green Star rating is blah, blah, blah, we've got X amount of energy that we could still save – that kind of information would be quite valuable for a lot of people.'* Participants identified many types of data that could potentially be revealed using this feature, however, P6 thought it would be more useful if the virtual model could provide more granular detail about the building, such as data about different parts of the building. For instance, the *'number of people in different floors and the energy used per floor so you can see the correlation.'*

Participants were also intrigued by the pseudo-physicality of the AR data visualisations. P1 asked if it was possible to interact with them directly: *'Can you touch on one of those data points in there?'* P6 found it interesting that the AR views of multiple participants were *'synchronised in space'*. Communicating to another participant they explained, *'here, you should see me pointing at the same thing that I'm pointing at, which is the third one down on [building X]'* **(C3)**. However, P2 pointed out a potential downside of the engagement of the AR view is that it can present a distraction from collaborators: *'like I can see you guys, but when stuff's up I'm not really paying attention.'*

5.3.2 Different Data Encodings for Different Users

Participants were quick to point out that multiple different data encodings are required to support different user roles, knowledge sets and problems **(C3, C4)**. For instance, there are multiple options for our building energy visualisation: *'Kilowatt hours is about how much electricity you are actually using over time'* (P2) and is useful for *'billing purposes'* (P5) or to tell you *'which of the buildings are consuming the most energy over time'* (P2). Conversely, *'absolute peak ... would give you an interesting look at where the high loads are'* (P2), and *'allows* *you to plan for the power flow going into the building or out of the building. So then you can plan your networks'*.

Similarly, the given time period is useful for different purposes. For instance at the network infrastructure level, engineers in different cases might be interested in the *'maximum capacity of the transformer'* on a given day (P6), a *'heat map... for both the transformer and the line'* (P7), or the instantaneous readings at the transformer, *'so you can see the fault and so on'* (P7). However, members of the campus microgrid project group stated they are more interested in historical data, for instance to identify constraints in the system at a high level: *this is helping you understand where those constraints are that you need to target or what's actually been going on.'* (P1).

5.3.3 Challenges of Novelty: Balancing Engagement

Participants overwhelmingly found the system highly engaging, and were excited about such a system's potential to impress external stakeholders **(C1-C4)**. Several participants described the animated tabletop visualisation as *'cool'*, an in particular found the 3D AR visualisation interesting: *'futuristic'*, and *'it's like, wow, amazing'* (P6). However, participants also noted that the multiple visualisations are potentially visually overwhelming, for instance it *'seems a little bit confusing'* (P6), and *'something that's confusing me is a lot of stacks and dots and stuff... it's quite a lot of colours and information. How do you make sense of it?... knowing what's what and what that information means'*. Conversely, participants were comfortable with the familiar 2D charts, even though they were displayed in interstitial space using the AR view, e.g. *'maybe that's because I'm used to that kind of illustration'* (P5). However, when we pointed out that the familiar 2D chart of solar maximum was linked to the 3D view of the solar generation, participants responded that this would assist with their interpretation of the 3D data.

Despite challenges in interpretation of the 3D visualisations, participants understood their potential benefit. In our early iteration of solar energy we experimented with using width to represent solar generation, as it would be proportional to the area of the photovoltaic panels. However P6 commented that by not using height as an encoding *'it kind of feels like you're wasting a dimension'*.

Overall, care needs to be taken when introducing novel visualisations, either through elicitation studies to find commonly understandable visualisations (e.g. [62]), or by providing instructive content [56] to assist new users in learning how to interpret them.

5.3.4 User Acceptance

To supplement the questionnaire results we received from the 4 participants of our final feedback session, we distributed the Van der Laan questionnaire to 16 attendees who subsequently attended a demonstration of Uplift at a local energy conference. Perceived Usefulness and Satisfaction are measured by taking the mean score of each dimension (5 questions for Usefulness and 4 for Satisfaction) on a 5-point scale, from -2 to +2. Overall scores were positive, but there was a small difference between the groups, with experts rating the system as slightly less useful: conference attendees had mean scores of 1.44 (Cronbach's Alpha, $\alpha = 0.29$) and 1.36 ($\alpha = 0.83$) for Usefulness and Satisfaction, respectively, while experts mean scores were 1.10 ($\alpha = 0.76$) and 1.38 ($\alpha = 0.77$). However, a low α value for conference attendees resulted from a greater variance in their scores. Nevertheless, results indicate that participants appreciated Uplift and found our prototype both potentially useful for the use cases we demonstrated and satisfying.

5.4 Future Improvements for Uplift and Similar Systems

Our experience building Uplift, along with lessons learned from our demonstration of the system and analysis of the expert feedback sessions, revealed several interesting directions for future research.

First, our current prototype explored only a few of the available use cases that we learned about in our elicitation with microgrid experts. As the project continues, more data will become available from the microgrid for use in our system, including real-time systems data, such as building occupancy, system loads, energy-related financial transactions, etc. Incorporation of these data into Uplift will offer opportunities to explore novel data encodings and interactions that smoothly integrate information from multiple data layers. It will also allow us to evaluate further use cases with a wider variety of system users and experts from different related research areas.

To make the system more self-contained and more widely deployable, we would like to explore methods for tracking widgets without the Vicon system, for instance TouchTokens [41] or Model tracking with Vuforia [9] . While we expect we will continue to find the external object tracking useful for prototyping of interactions, a self-contained system will allow us to conduct longer-term studies of the system in real-world situations. For instance, it would be interesting to deploy similar systems in the boardroom of an energy company to investigate the use of CCVA between operators and executives, or to adapt the system for use in other domains such as civic planning.

We would also like to expand the potential use cases for systems such as Uplift by supplementing the exploration of historical data with new features for simulation, forecasting, and data storytelling. This would result in a powerful system that would allow users to better understand and demonstrate complex systems, for instance how energy consumption would change if a new building or battery storage were added. Authoring features to create an interactive 'sandbox' will allow users to quickly prototype and demonstrate scenarios to other groups of users to facilitate understanding and assist decision-making.

6 Conclusion

In this paper, we presented Uplift, a prototype system aimed at supporting CCVA. In a co-design process with smart grid experts we identified a list of design criteria to support CCVA. Our prototype developments were informed by outputs of interviews and an elicitation workshop, which included a variety of user needs, relevant topics, and goals for visualisation of microgrid data. Workshop participants were enthusiastic about a physical 3D campus model, which inspired the model that provided a tangible physical referent in the centerpiece in our prototype.

In a series of expert feedback sessions, participants were highly receptive to Uplift. We learned about several potential applications where microgrid operators and project managers could benefit from similar systems, such as breaking down knowledge silos between occupants and users, data storytelling to educate energy users, and providing a intuitive overview for identifying patterns such as peak-demand or correlation form data across a large network. Participants also found the tangible and AR features of Uplift engaging, while making us aware of specific challenges that need to be considered when presenting data with novel technologies.

Our co-design participants provided knowledge and insights related to their expertise in the smart grid domain, however, we believe our formalisation of CCVA and takeaways from our findings are applicable to other domains. For instance the construction industry could overlay building sensor and occupancy data on a physical model through the planning, building, and maintenance stages of a building lifecycle. On a larger scale, planning, optimisation, and monitoring data can be visualised over transport networks to facilitate problem solving and decision making. In general, we believe future systems similar to Uplift will benefit collaboration in domains that rely on analysis of complex systems data in conjunction with spatial data or assets.

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