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Bridging Tangible and Virtual Realities: Computational Procedures for Data-Informed Participatory Processes

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Abstract: Driven by technological advances, growing amounts of available data, and an emergent need for participatory processes, landscape architecture is witnessing a moment of disruption whereby formerly separated areas of operation become increasingly connected. While distinctions between various aspects of the design process are diminishing, a need for a novel, more inclusive toolset arises. The 'tangible table' paradigm is an attempt at combining intuitive ways of physical modelling with data-driven design strategies and the interactive simulation of naturally occurring phenomena. Despite its existence for more than 20 years, tangible tables have mainly focused on very specific workflows and therefore have not found wider adoption in landscape architectural practice or education. We list the limitations of previous implementations and introduce a novel software solution aimed at popularizing tangible table setups. Our software is embedded in a widespread visual programming environment, which allows for straightforward augmentation of physical models with computational design techniques. Using a week-long PhD course as a case study, we demonstrate the usefulness of the proposed software and its potential applications to solving various landscape architectural challenges through increased emphasis on participatory processes.

Keywords: Participatory Design, Tangible Table, Computational Design, Grasshopper, SandWorm

1 Introduction

Climate change, accelerating urbanization and growing social inequity have become increasingly apparent challenges which force us to redesign our communities and enable them to adapt to varying environmental conditions. United Nation's Sustainable Development Goal 11 – *Make cities and human settlements inclusive, safe, resilient and* sustainable – reflects this necessity while also stressing the need to consider multiple stakeholders' interests in the process. To ensure a common definition of success in urban design, the figurative walls between disciplines and departments must be torn down, and better multi-disciplinary partnerships introduced. Landscape architects, through the nature of their work with both environmental and cultural systems, are uniquely equipped for this task (MOSSBERGER et al. 2008). We bring different and often competing interests together to address complex social and ecological problems. This notion of a collaborative and integrated planning process aimed at delivering the most optimal design solutions is the foundational principle of the Geodesign framework. At its core, it is a land design and planning method which couples the creation of design proposals with impact simulations informed by geographic contexts, data, and systems thinking, all of which is supported by digital technology (BOLTON et al. 2018).

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Landscape architecture, however, has a rather poor track record of embracing new technological paradigms and tends to lag behind related disciplines, when it comes to adoption of novel workflows and tools. Other industries such as product design or architecture benefit from distinctive technological advancements in the fields of design, fabrication and construction to enable new forms of expression and achieve higher level of performance (CANTRELL & MEKIES 2018). Simultaneously, data collection technologies have become abundant and most aspects of our everyday lives are tracked and evaluated in real-time. Increasing quantity of data, however, doesn't necessarily translate to meaningful information (FRICKER et al. 2015). The real challenge ahead of the industry is to carefully select and analyze reliable data to then integrate the insights into a dynamic and intelligently adaptive system for urban planning (SCHWAB 2016).

This necessity creates a shift towards different planning and design methods, whereby formerly distinct areas of operation become increasingly connected and accessible in ways previously not possible. Differences between scales, disciplines, physical and virtual realities, industry professionals and the open public, are diminishing as technology helps span a bridge between these fields (LOUKISSAS 2019). New methods and planning tools are therefore needed to translate and integrate the diverse outcomes of multidisciplinary processes into coherent design proposals. They should have the capacity to integrate input from different data sources and to simulate their impact on possible planning strategies. Such interactive simulations help in visualizing planning and design processes, rendering them more transparent and promoting accountability amongst stakeholders (POND et al. 2012).

The 'tangible table' or 'augmented reality sandbox' is one attempt to create a framework aimed at simplifying the complexity of the design process through introduction of intuitive, manual modes of data input through physical media, and its subsequent simulation and visualization with digital means (PETRASOVA 2018). First proposed around 20 years ago, it was initially developed for urban planning and design (UNDERKOFFLER 1999, DO 2002) but has since found a variety of different applications. These include interactive instruments used for educational exhibitions (REED 2014); tools for large-scale geospatial analysis (PETRASOVA 2018); specialised simulations of river dynamics or landslide processes (CANTRELL & HOLZMAN 2014, HURKXKENS 2019); and even arcane devices to promote well-being by fostering mindfulness (ROO 2017).

This variety of applications necessitates the use of diverse media such as different types of sand (REED 2014), LEGO blocks (ALONSO 2018), pneumatically controlled shape displays (LEITHINGER 2015), or sheets of paper with visual tags (DYNAMICLAND 2018). Modes of user-interaction with the physical and digital realities also range from direct manipulation, through robotically controlled material extraction or deposition (CANTRELL 2015, HURKXKENS 2019), gesture recognition (REED 2014) to real-time scanning of printed code snippets (DYNAMICLAND 2018). Figure 1 presents a brief overview of how this variety manifests itself in a physical form.

Despite the formal diversity of various realizations of the tangible table principle, the majority seems to share a common characteristic – they were conceived to perform a single, often very specialized, function. As a result, they frequently require dedicated hardware with separate operating systems to run on and are applied in isolation from industry standard sketching, modelling and drafting workflows. Accordingly, the flow of data between stakeholders and across various design stages is disrupted and iterative processes are discouraged. This type of format puts further emphasis on individual disciplines and siloed thinking rather than fostering the multi-disciplinary collaboration – that is a necessary requirement for truly participatory processes.

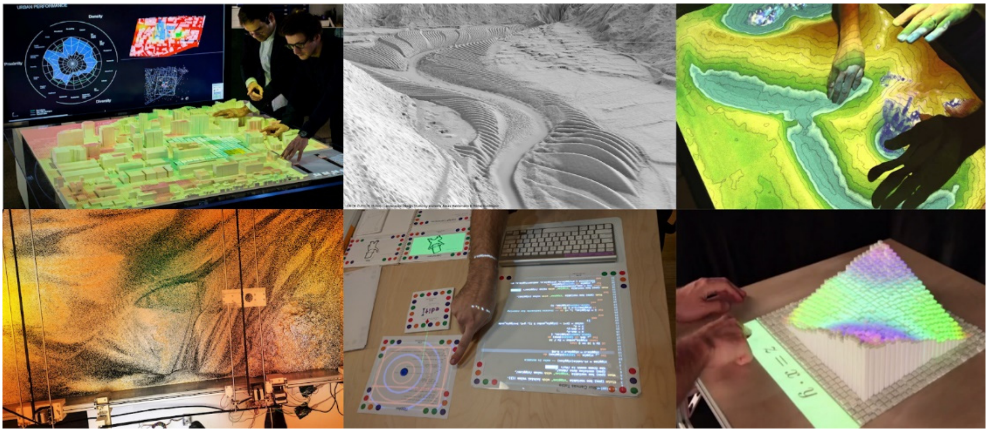

Fig. 1: The concept of a tangible table encompasses a wide variety of specialized applications (Upper row from left to right: MIT Media Lab, ETH Zürich, UC Davis; Lower row from left to right: Cornell University, Dynamicland, MIT Media Lab)

While acknowledging that tools and methods need to be developed in relation to a given task's complexity, scale and setting, we propose a more generic application format that can be used for different purposes and accommodate varying user backgrounds and data packages. Our goal is to advance participatory design processes through introduction of a platform that can seamlessly merge different design phases by leveraging tangible and virtual instruments and allow for data-informed design and decision-making methods.

2 Current Challenges

One problem in creating meaningful participatory involvement is that existing representational tools are not well suited for allowing diverse interests groups to understand, evaluate, and provide feedback on the benefits and tradeoffs of potential design decisions. Recent years, however, have seen the emergence of new cooperative planning tools, made possible by the growing availability of interactive computing technologies. By implementing concepts such as digital twins or virtual, augmented and mixed realities, these solutions promise to facilitate discourse between stakeholders in a way that could transform public participation. The idea of a tangible table constitutes one example of such attempts. This paradigm of combining the intuitive manipulation of physical media with interactive data analysis – despite its potential benefits to multiple domains – has not found wider adoption in landscape architectural practice or education. Tangible tables are seemingly pursued either as demonstration setups for exhibition, or as highly customized systems for specific research endeavors. They are rarely used as general-purpose design tools. This niche status stems from several technological and methodological constraints which we identify and describe in this chapter.

2.1 Limitation 1: Flexibility & Integration

Existing methods for combining physical modelling with computationally augmented analysis either act as stand-alone pieces of software (REED 2014, CANTRELL 2015), or are embedded in Geographic Information System (GIS) applications (PETRASOVA 2018) without direct links to Computer Aided Design (CAD) drafting environments. The majority also runs on Linux-based operating systems, whereas most of the software used in landscape architectural projects operates on Windows or OSX. As a result, these setups are not immediately compatible with common design development workflows and require additional effort to be adapted to project specific constraints or find application in production environments.

2.2 Limitation 2: Hardware

Hardware constraints are a most common limiting factor for any process related to computational design, both in terms of the quality of data which can be collected and the quantities which can be processed and analysed in reasonable timeframes. Given the constant advancement of technology, hardware is also typically subject to most frequent update cycles and can quickly become obsolete. Subsequent generations of devices typically outperform their predecessors and allow for higher accuracy and overall efficiency gains in the design process resulting from increased processing power.

Most existing tangible tables use either the first or second generation of Microsoft's Kinect sensors to obtain depth scans of underlying objects. While easily accessible and affordable, this product line was first introduced in 2010 and comes with an error margin in the scanned data of approximately 10-15 millimeters in the vertical direction (WASENMÜLLER 2016). Various attempts to overcome these limitations exist, mostly relying on spatial and temporal averaging algorithms (REED 2014, PETRASOVA 2018). The resulting scan resolution and accuracy, however, are still insufficient for precise 3D reconstruction of detailed landscape architectural models.

2.3 Limitation 3: Accuracy & Scale

Previous implementations typically operate in city or geographic scales and provide a rather general overview of social, economic and physical characteristics of urban areas (ALONSO 2018), topographical site-conditions or prevailing geological processes (PETRASOVA 2018). Design endeavors in such large scales naturally gravitate towards higher levels of abstraction and simplified representations to visualize various phenomena occurring in the real world. To support this way of thinking and encourage broader stakeholder engagement, the physical modelling media are purposefully chosen to be familiar to wide range of users, intuitive to manipulate and abstract in their nature (e. g. sand or LEGO blocks). This decision becomes disadvantageous when tangible tables are applied to design at smaller scales, where precise form-finding constitutes a more prominent concern in the design process. The modelling media are simply not accurate enough to depict the high-fidelity forms commonly needed for detailed development of most landscape architectural projects. Combined with aforementioned inaccuracies of scanning equipment, this limits the use of tangible tables to very early design stages, where a general understanding of the design direction is valued more than its precise representation.

3 Implementation

We developed SandWorm to address the main challenge of integration within established design workflows, where seamless data exchange between various stakeholders and applications is key. In addressing this main challenge, Sandworm also aims to advance and popularize the tangible table paradigm within the domain of landscape architecture. While previous implementations worked primarily as specialized, stand-alone pieces of software, SandWorm is designed to be very easy to contextually adapt and integrate. To this end, it was developed as a plug-in for Grasshopper – a visual programming language and environment that runs within the CAD program Rhinoceros 3D.

SandWorm's integration with Grasshopper allows users to leverage a plethora of existing, mostly free plugins. The entire ecosystem available at the time of this writing encompasses more than 100 applications grouped in the categories of Environmental Design, Urban Planning & City Modelling, Civil Engineering and Landscape Architecture. Figure 2 highlights a few selected domain specific ones, with special emphasis on Groundhog (BELESKY 2017), Bison (BISON 2019) and Docofossor (HURKXKENS 2019), which offer a comprehensive set of tools for digital topographic modelling across various scales, while also providing pre-defined routines for industry-standard analysis methods. SandWorm contributes to this ecosystem by supplying real-time (up to 30 frames per second) scans of physical models, translated to a 2.5D quad-mesh terrain representation suitable for downstream analysis. The plugin ships with built-in methods to visualize elevation, contour lines, slope, aspect and water flow, all highly optimized for real-time user interaction.

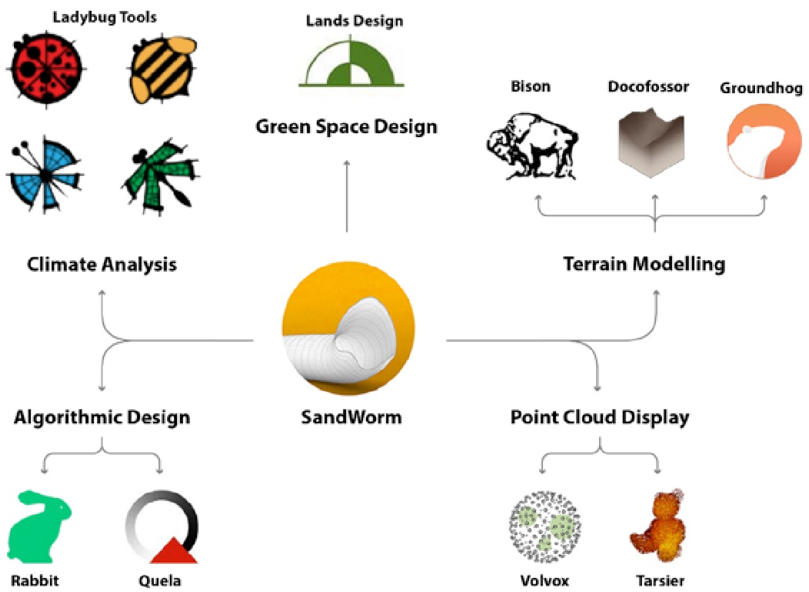

Fig. 2: A small selection of Grasshopper plugins suitable for computational design applications in the field of landscape architecture. Grouping proposed by the authors.

To overcome the hardware limitations of previous tangible table implementations, SandWorm was designed to leverage data output from the Kinect for Azure sensor that was released in the second half of 2019. Its increased accuracy and greater depth camera resolution (1024 × 1024 pixels versus 512 × 424 of the Kinect 2) were critical for operation at smaller scales and improved interaction with the kinds of physical models typically produced during design development. To maintain acceptable levels of interactivity, while dealing with almost fivefold number of pixels, we had to employ several low-level software optimizations to the graphics pipeline. As a result, outputs from SandWorm running on high-performing PCs are continuously rendered with a low latency interval of less than 10ms at full depth resolution. This outperforms general-purpose plugins for point-cloud capture in Grasshopper such as Firefly (FIREFLY 2014) or Tarsier (TARSIER 2015) and frees up computational resources for downstream analysis or visualization.

4 Validation

Methodologies that see a design develop as a dynamic entity assembled from a series of generative rules are increasingly common in the landscape architectural profession (WALLISS & RAHMANN 2016). By defining parameters that account for the temporality, uncertainty, or dynamism of landscape systems, users can begin to make these phenomena truly operative within the design process. While this approach holds a lot of promise, its pedagogy continues to pose a challenge (FRICKER 2013, BELESKY 2018). By combining the intuitive user interface of a tangible table with the (relatively) accessible scripting interface offered by Grasshopper, SandWorm provides landscape architects with a low entry threshold for working between computational design and tangible modelling methods. To validate this assumption, the SandWorm plugin was tested during a week-long PhD workshop focusing on 'Geodesign Technologies'. The interdisciplinary workshop was conducted in August 2019 at The University of Copenhagen in collaboration with the Aalto University and was open to national and international PhD students. Nine PhD Fellows, four Master's students, two researchers, and one practitioner at an architectural studio participated in the workshop; representing a range of countries – Finland, Germany, Denmark, Switzerland, and the Czech Republic.

The objective of the workshop was to explore and discuss computational design methods that go beyond the manually crafted nature of static physical models or the well-established digital techniques available within common GIS and CAD environments. During the workshop, we reflected on the potential of new forms of dynamic representation – both physical and digital – that emerging technologies enable and their potential ramifications on participatory planning processes.

A key focus of this exploration was to develop an immediate connection between the conceptual aim of a given design task and computational technologies leveraged to establish designers' perception of a given site. The design approach was supported by the *Four Trace Concepts in Landscape Architecture* described by GIROT (2009): *Landing* (perceiving, learning, and registration of the site); *Grounding* (realizing the site's problems and potentials in relation to the design program); *Finding* (formulation of design proposals), and *Founding* (assessment of design proposals).

4.1 Design Task

The site of the design test-case was a one-hectare parking area at the University of Copenhagen's campus. The area will likely see a substantial increase in the number of visitors and passers-through as the landscape will open up to the surrounding urban fabric and a potentially daylighted river.

Various technologies played different roles along the week, including portable LIDAR scanning and geolocated photo capturing, SandWorm/Rhino/Grasshopper during *Landing* and *Grounding*. Rhino/Grasshopper were applied at the *Finding* stage. *Founding* was devised digitally, using on site Augmented/Mixed Reality projections, and physically with final-quality presentation models in the sandbox. The translation of digital design ideas to tangible scale models happened via a robotic arm controlled by custom Grasshopper scripts (Fig. 3).

Fig. 3: Human-robot interaction at the tangible table: Testing of abstract design patterns on their performance with sound and water. Student project by: Ayda Grisiute, Sebastian Juul Hansen, Louise Karlsen, Barbara Kostanjšek.

Using SandWorm to capture the design patterns hand-sculpted in the sandbox allowed for real-time evaluation and an iterative approach in the early stages of the design process. Participants – aided by projection mapping, augmented reality, real-time data assessment, agent-based modelling and live hydraulic simulations – were able to rapidly develop their design strategies and intuitively integrate dynamic models of landscape processes into their proposals. The relatively flat learning curve of Grasshopper's visual scripting environment enabled participants of varying background and knowledge to meaningfully contribute from day one, and successfully connect traditional landscape architecture with systems thinking (FRICKER et al. 2019).

Plugins used by students include (see Figure 2 for domain specific grouping):

1) SandWorm – Tangible/digital interaction: terrain mesh creation and analysis: elevations, contours, slope, aspect
2) Bison – Analysis: spot elevations, shade, viewshed, watershed, flowlines, cut and fill
3) Docofossor – Terrain modelling: roads, paths, flat surfaces, swales, streams
4) Groundhog – Analysis: shortest path analysis
5) Firefly – Visualization: sound visualization, frequency spectrum
6) Quelea – Simulation: pedestrian behavior

Over the course of five days, students articulated the site-specific parameters (environmental, user-driven and design driven data) within the overall system and translated their basic behavior into integrated and responsive design patterns. Elements such as sound distribution, stormwater flow or human interaction patterns were simulated using Grasshopper and visualized through the robotic interaction in the sandbox. The final three designs were developed in interdisciplinary teams and focused on:

Sound: Site-specific sound sources acted as a conceptual backbone for the design. By custom-scripting an interactive sound visualization tool on top of Grasshopper plugin Firefly, participants were able to visualize the distribution of music and traffic noise in relation to the existing terrain (Figure 4). To further develop the model, real-time validation of the generated terrain solutions and its performance in relation to sound propagation would be required. Additionally, a field survey confronting the simulated results with actual measurements on site could be performed.

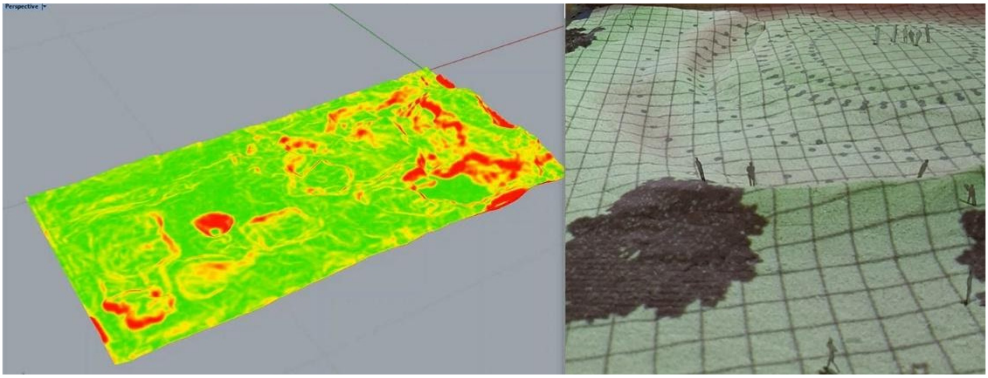

Fig. 4: Translation of site-specific soundscape as design driver for proposed interaction zones on site. Student project by: Ry Mette-Sofie Rybak, Kim DaeYong, Radim Klepáník, Jozef Sedlacek.

Agent-based modelling: The focus of this design was the evaluation of a human-centred outdoor space shaped by the path network and its influence on the flow of people, and their dynamic behaviour. By using the Grasshopper plugin Quela, the students were able to interactively simulate projected movement patterns reacting to real-time changes within the sandbox. Interactive analysis and visualization of individual agents' 3D viewsheds was made possible by means of the Grasshopper plugin Bison. The model could be further improved if realistic parameters for the number of entering visitors at different gates (assessed by means of e. g. counting stations) and their spatial behaviour in the park could be obtained (e. g. GPS tracks).

Water: The design process was enhanced through intuitive terrain modelling, supported by real-time cut and fill calculations, simplified hydraulic modelling using Bison and custom-scripted, particle-based flow simulation (Figure 5). Validation and finalization of the terrain model was achieved in Grasshopper using Docofossor in conjunction with Rhino's built-in mesh editing tools. Further development of the model could involve performing a 2D analysis with HEC-RAS to gain a more thorough understanding of hydraulic conditions on site.

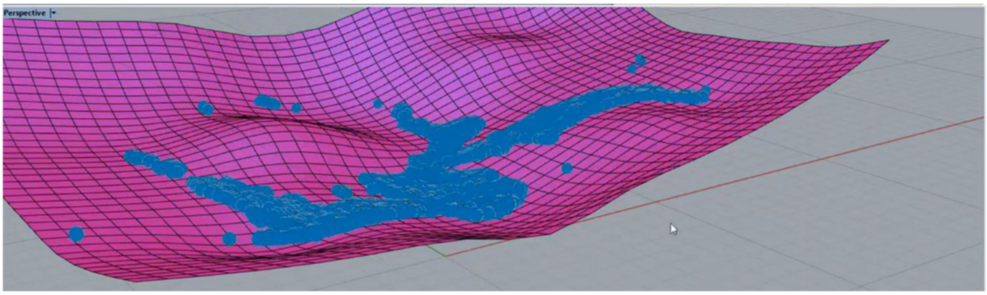

Fig. 5: A real-time visualization of surface water flows and pooling areas provides an overview of hydrological conditions on site. By directly revealing the dynamic behaviour of stormwater flow, workshop participants could collaboratively evaluate their designs against this criterion. Student project by: Rachel Subtil, Mette Juhl Jessen, Kristine Holten-Andersen, Johann Junghardt.

4.2 Course Assessment

After the workshop, participants were asked to assess their experience with the technologies and methods applied during the week (the transcript is available from the authors). Several expressed satisfaction with the tangible table setup as an intuitive and easy-to-use way of learning and understanding complex relationships between different elements of landscape architectural projects. As one student claimed *'[…] Landing with the sandbox was just something – we do models by hands, but it is never so fluent. […] a very different experience from drawing in Rhino'*.

Potential applications of available 3rd party plugins and the ease of creating custom scripts in the Grasshopper environment have resulted in positive feedback from the participants. Several, with good background in spatial modelling in GIS, expressed satisfaction with the intuitive use of spatial analysis tools embedded in a full 3D modelling environment. As stated by one student *'[…] maybe it is the combination of the digital model, the sandbox and the components in Rhino which allowed me to create some of these analyses, which I really never felt comfortable with in GIS'*.

In general, participants perceived the tangible table setup coupled with 3D modelling and computational design environments as a gain for collaboration and participation. As expressed by one student: *'Those technologies lower the barrier for the ordinary people, and […] for us (as professionals) as well'*. This observation was highlighted both referring to presenting final design proposals: *'[…] it is a really nice tool for participation if you have a finished design […] and you want people's reaction'* and sketching in the early stages of the design process: *'[…] as a landscape architect, I would definitely use it for rough massing and early in the design phase'*.

Finally, the participants were asked how their newly gained exposure to participatory design methods augmented by digital technologies would influence their approach to their work. The consensus seemed to be, that this framework introduces *'[…] a whole new process. Makes us think differently, creatively'*.

5 Discussion

Starting from the premise that meaningful public engagement is fundamental to successful planning and design we proposed a software solution, which is aimed at popularizing the tangible table paradigm during participatory design processes. As tangible tables already provide an intuitive means of designing landform (PETRASOVA 2018) and urban layouts (ALONSO 2018), we believe that they hold potential as a broader paradigm given, they can include a more comprehensive set of tools which can directly augment landscape architectural design techniques alongside established geospatial analytics. However, building these new tools would require the tangible table paradigm to act like a platform, or a tool-for-making-tools, for it to advance beyond its present niche applications. Therefore, we chose to embed our solution in a widespread visual programming environment, allowing for straightforward augmentation of physical models with computational design techniques.

Participatory processes exist on something of a spectrum – there is the intuitive and tactile nature of the table that makes it participatory. But, the flexibility of the parametric design environment also means that it becomes participatory in another sense – its users can take an active role in the seemingly infinite creative potential of the digital system. Landscape architects typically work in computer-aided design applications that are foremost developed for the needs of architects, civil engineers or other professions. As a result, our tools are rather generic and do little to cater to the nature of landscapes and the disciplinary knowledge of how we design them. The PhD workshop demonstrated, how our setup allows practitioners of various backgrounds to make better use of the 'physical' participation in the table as it can be adapted to different design challenges with relative ease.

The adaptive nature of the environment allows users to develop their own modelling procedures that leverage Grasshopper's existing plugin ecosystem alongside their own parametric logics. Crucially, this element of flexibility allows for tangible tables to be customized in terms of their hardware and software – affording users both the advantages in intuition and tactility of the former, while opening the dynamism and power of the latter. As a result, notions of 'synthetic ecologies' (CANTRELL & HOLZMAN 2014) or 'dynamic patterns' (M'CLOSKEY & VANDERSYS 2017) become frameworks that can operate as both a conceptual guide, a computational procedure, and a capacity embedded in a tangible model.

Of the three main challenges preventing wider adoption of tangible tables identified in chapter 2 of this paper, incorporating SandWorm with the Rhino/Grasshopper environment solves the one of flexibility and integration. Low-level optimizations in the code and leveraging the Kinect for Azure sensor, help partially overcome the hardware limitations related to resolution and scanning accuracy required to capture physical models with acceptable precision. Technological advancement in this field will, however, continue to happen and future hardware will most likely be able to deliver higher quality results. The limitation of scale is primary a result of the inherent nature of modelling media chosen for the tangible interaction and remains to be addressed on a case-by-case base.

To achieve the goal of increased adoption of the tangible table paradigm in participatory processes, much more effort is needed on the documentation side. Our hope is that more case studies, like the PhD workshop described in this paper, will be conducted and will serve as valuable ways to publicise the possibilities of this approach that others can pick up and extend upon.

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