ADAPTING A DIGITAL TWIN TO ENABLE REAL-TIME WATER SENSITIVE URBAN DESIGN DECISION-MAKING

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ABSTRACT:

Landscape architects and urban designers are often tasked with decision-making about implementation of flood moderating measures in urban renewal projects. These decisions require consideration of complex, interdependent existing and proposed infrastructure, and must be informed by data and modelling from multiple disciplines such as hydrologists, transport engineers and urban planners. Here we describe the challenges of integrating these data and modelling from both GIS and BIM sources, into a framework that could support flood moderation decision-making, embedded within a spatially enabled Digital Twin. Our findings outline some of the considerable adjustments to future data collection methods that will be required to enable such a decision-support framework. Furthermore, we outline the requirements of the framework for employability in stakeholders and community decision-making forums. We test this framework on a large-scale urban renewal precinct in Melbourne Australia, with well recognised current and future flooding issues.

1. INTRODUCTION

1.1 Urban flood infrastructure decision-making

Urban renewal projects present landscape architects, urban designers, engineers and planners with design decision-making that must address challenging environmental conditions, pressures to meet desirable housing density quotas, transport needs, and a mixture of built and yet to be built entities and infrastructure (Newman & Kenworthy, 2006). The interaction of slow changes such as weather conditions and urbanisation processes, make future infrastructure resilience requirements difficult to determine through assessment of historic events and existing conditions alone. Thus, innovative modelling methodologies such as Digital Twins and Decision-support systems must be developed to address this task.

In urban renewal projects on land subject to inundation, the design of stormwater infrastructure, suitable for both current and future weather conditions, is a critical problem (Sprague & Prenger-Berninghoff, 2019). The infrastructure required is often costly, spatially demanding, and there are many unknown facets associated with changing rainfall patterns, storm intensity and evolving urban form. (Cea & Costabile, 2022; Urich et al., 2013). Evidence-based, data informed decision-making, becomes essential for flood adaptation planning in these projects. However, consideration of flooding presents particularly complex, substantially unresolved challenges within digital environments, as it sits at the nexus between 3D terrain, existing street networks, existing and proposed built form, multidisciplinary data collection practices and community consultation visualisation needs (Fuerst & Warren-Myers, 2021; Yan et al., 2019).

In addition, urban streets are considered important public spaces that substantially contribute to the economic and social success or failure of urban developments (Desyllas & Ward, 2009). The design of streets is rarely carried out in a 'black box', and in line with the Geneva convention regarding consultation and decision-making processes, must be undertaken with the inclusion of input from the community and stakeholders, using disciplinary agnostic communication methods suitable for workshop environments (Cousins, 2017; VAGO, 2017).

1.2 Digital Twins and Decision-support systems

The origins of Digital Twins (DT), lie in monitoring the performance of real-world entities such as off-shore oil rigs, remote buildings and more recently whole urban environments (Batty, 2018; Chaplin et al., 2020; Grieves, 2019). While urban scale DTs were originally conceived to enable 'now casting' for optimal, smart infrastructure action and management, responsive to the inflow of detailed real-time monitoring data from their physical counterpart, their application is rapidly expanding beyond this use (Papyshev & Yarime, 2021). Recognition of the intersections between the physical and digital infrastructure of DTs, and those of Decision Support Systems (DSS), particularly urban scale DTs and DSS designed to support city scale decision-making is growing (Chaplin et al., 2020).

Urban scale DTs and DSS, face many similar data integration challenges, they both leverage historic and current data sources, require a high-quality user experience, and they must integrate 2D geospatial information (GIS) data and 3D building information (BIM) models (Deng et al., 2021). However, decisions undertaken within strategic long-term urban design and planning, operate on a much longer time scale than the immediate

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management decision-making DTs were originally conceived to assist. Adapting DT infrastructure, to enable urban design decision-making processes, that typically consist of a series of “What-if” questions, and require modifications of current urban environments for testing, evaluating, and assessing various design scenarios, presents a series of challenges that can, if improperly implemented, break the nexus between data streams and the original or existing environment from where it was collected.

Despite these challenges, the potential to tailor DT infrastructure, to support urban design decision-making, is enticing, and nowhere more so, than for large scale, complex urban renewal projects that involve multidisciplinary modelling and data.
This project brought together an interdisciplinary team of landscape architects, urban designers, Digital Twin (DT) developers, planners, engineers, and integrated water management professionals to investigate the complex challenges involved in developing tools to meet these decision-making needs.

1.3 Aim

In this study, we aimed to leverage an existing spatially enabled DT infrastructure, produced and maintained by the Faculty of Engineering and Information Technology at the University of Melbourne. We sought to tailor this DT to produce a prototype framework for flood infrastructure design decision-support and visualisation for urban renewal projects, suitable for use within cross disciplinary and community consultation workshop forums. We tested the prototype on a study area of a 5.5kms^2 urban renewal precinct in Melbourne, Victoria, with well-known flooding issues from multiple sources.

1.4 Method

Our method involved identification of relevant spatial data that might inform strategic water sensitive urban design decision-making and to bring these together within the DT infrastructure. Data sources ranged from GIS based records from transport authorities (road centre lines and casements), planning authorities (land ownership and greenspace), drainage engineering professionals (kerb lines), to BIM and or non-spatial data representing proposed building design massing models (proposed heights and setbacks) and street layouts. Critically, these data were then combined with flood modelling outputs, including sub catchment analysis developed by integrated stormwater professionals, for assessing existing and proposed surface-based stormwater storage infrastructure under different future conditions. Through the process of normalising these disparate data we outlined the challenges and potential approaches to their alteration, modification, and usability in a Digital Twin environment.

1.5 What data is needed for flood responsive urban design

Multiple sources of flooding

Flood originates from three primary sources. River or fluvial flood arises due to swollen riverbanks, coastal flood arises through sea level rise, tides and storm surge, while pluvial flood arises through build-up of surface water as overland flow during high intensity storms that overwhelm the underground pit and pipe system.

Moderation strategies for each of these types of flood are vastly different. While coastal and river flooding require largescale interventions close to the interface between land and waterbody, pluvial flooding requires a distributed network of rainfall detention mechanisms, that slow the speed of surface water, allowing time for the pipe and pit system to recover (Burns et al., 2015; Urich & Rauch, 2014). This distributed stormwater detention infrastructure can vary in form, from rain gardens and rain tanks located in private land to roadside swales and bio-retention pits beneath permeable surfaces in public land.

Multiple types of flood modelling

While many places suffer compound flooding from all three sources, each type must still be modelled and understood individually. Regardless of source, flood modelling involves ‘time series’ dependant, simulations of storm events, to output flood speed, velocity, extent, and flow. While faster methods are evolving, these models have been traditionally computationally expensive and slow to run (Wu et al., 2018). Furthermore, the required underlying sub-catchment capacity model is generally calculated in decoupled GIS software using a 2.5 and or 3D digital elevation model or digital surface model (DEM or DSM).

Flood responsive urban design decision making

Flood responsive planning and design means putting the right interventions in the right locations. For urban developments with high levels of private land ownership, flood moderating infrastructure often needs to be accommodated within public spaces, due to lack of overall network control associated with block level interventions on private land (Burns et al., 2015). In these projects, achieving the required water storage capacity entirely within intensively used public spaces such as parks and roads can mean complex multidisciplinary negotiations. For example, proposed parks may need to be located over sub-catchment low points, or along water body edges, so they also act as strategic detention ponds during flood events and streetscapes may need spatial adjustment to reallocate space traditionally reserved for transport toward water detention.

What flood modelling information is needed

For emergency management the speed and velocity at which a given location might flood is critically important. However, for urban design decision-making and strategic planning, these factors are far less critical than overall flood extent, flow direction and sub catchment capacity calculation all of which can be visualised in simple 2D plan formats.

We used this standpoint to simplify our DT flood infrastructure decision-support framework. Using this 2D method of flood visualisation allowed us to exclude some of the issues associated with integration of proposed 3D objects (buildings) and 3D terrain inconsistencies (Tomkins & Lange, 2019; Yan et al., 2019), (refer **Figure *1***and **Figure *2***).

Figure 1: 2D visualisation of sub catchments within the study area site

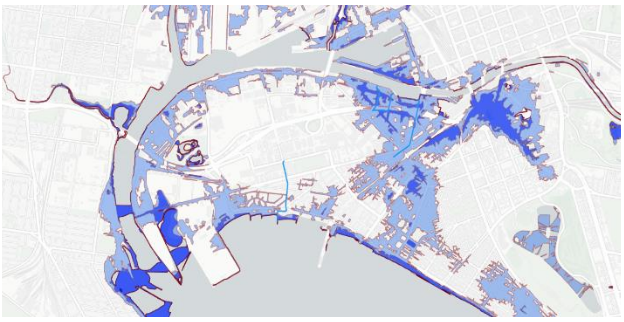

Figure 2: 2D visualisation of 2100 flood impact modelled scenario

1.6 The challenge of working with existing street data collection methods

For streets to be reconfigured to include storm water detention, conventional street design and drainage methods require quite radical alteration. For example, traditional, centrally cambered streets with side entry pits, might need to be 'inversed', to have central drainage, and or side detention pits (with or without trees), (refer **Figure *3*** and **Figure *4***). A change such as this demonstrates the substantial portion of street space that would need to be redistributed – away from vehicle transport systems, towards urban storm water infrastructure systems. For these negotiations to take place, detailed spatial road and street spatial data is required.

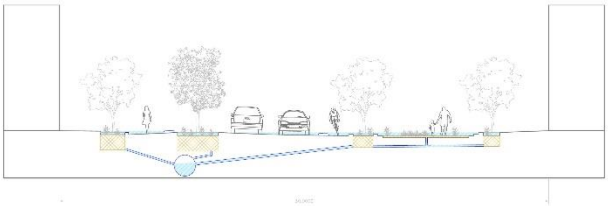

Figure 3: Shows an example of street reconfiguration, re-distributing the existing space to increase stormwater detention capacity within the streetscape. Image credit Anna Müeller

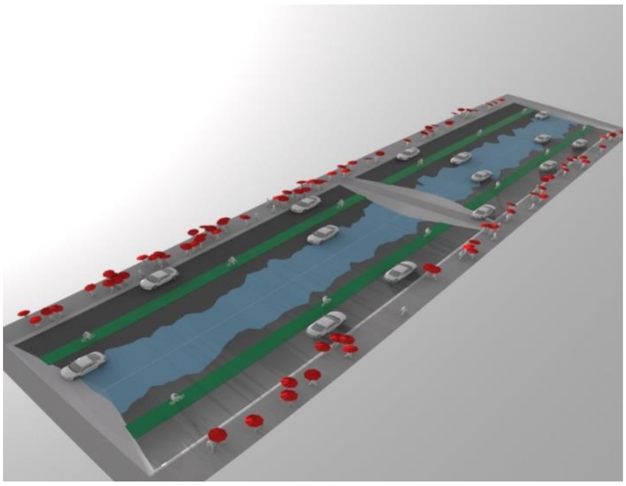

Figure 4: Shows how stormwater detention methods could radically alter streetscape configurations to accommodate future flood events. Image credit. Nano Langenheim

Existing street data

Street network data collection practices in Australia are undertaken by transport authorities. The format and focus of this data are developed based on relevance to transport planning, traffic flow modelling and maintenance of public assets. Common street network data collection processes use a 'street 'centre line' approach, divided into line segments or line sections at points where one street intersects with another. While this centreline data is useful for many aspects of transport modelling, spatially explicit attributes such as footpath location, and street widths that would be needed for negotiation of spatial redistribution such as street width and footpath location are routinely neglected.

Existing drainage network data

Drainage network data collection can often include some of the data missing from street networks such as kerb locations, however, these data are collected and maintained by entirely separate organisations and include ground survey levels of detail that make them computationally expensive to include in DTs. While spatial data is providing some promising advances in road edge recognition (Cheng et al., 2017), the reality for urban scale DT developers today, is that current road and drainage asset data collection processes are inadequate for creation of accurate streets within urban scale digital twin platforms.

Our approach to this issue was to manually measure street widths from Google Earth and to add this as an attribute column in the centreline data maintained by the local transport authority. Though this approach was highly manual it allowed a twofold benefit. Firstly, explicit street surface area calculation could be generated and second, streets could be buffered by width attribute to allow for realistic visualisation within the digital environment. This data was then imported into ESRI's City Engine platform to create roads with a more realistic appearance (i.e. lane markings).

Proposed street network data

In urban renewal projects, particularly in ex-industrial areas where block lengths are long, new streets are often a required part of the design. The integration of new street proposals into DT environments poses a further complication beyond a simple lack of attribute collection, as in the case of existing streets. The representation methods used for Urban design strategic visions or proposals, are rarely undertaken in spatially enabled platforms. They are often either hand drawn or created using non spatial representation platform such as Adobe Illustrator or Photoshop (White & Langenheim, 2018). While these images are evocative, efficient to produce and useful for community consultation forums, their capacity to be integrated into multidisciplinary design decision-making is limited.

Our approach to this issue was to develop a drawing tool within the DT platform dedicated to new road drawing, that allowed users to set a street width and length attribute. We also developed a download and edit function for the existing street network data, allowing users to download and edit sections of road that might require modification.

1.7 The challenge of working with proposals for urban form change and integration of BIM data

Though the existing DT has the capacity to visualise the 3D terrain through inclusion of a Z dimension DEM deformation, we selected a hybrid visual output that was both 2D map/ data visualisation, coupled with selected 3D BIM entities, important to the overall structure of the site. These entities included existing and proposed buildings and an existing multilevel complex freeway that ran through the entire length of the site.

While some buildings proposed for the site had already undergone the full planning approval process, and were thus available as detailed BIM models, these were not required to analyse the streetscape flood condition. We therefore included the proposed buildings as ‘massing models’, or proposed height limits represented through spatialised extrusions of building footprints. These were indicatively ‘textured’ in Autodesk 3Ds Max™ and brought into the DT framework via Cesium Ion ™, a 3D geospatial data platform, using the glTF file format, (refer **Figure *5***).

Figure 5: Complex model for multilevel freeway shown in Cesium Ion™ platform, modelled in and imported from Autodesk 3Ds Max using glTF format. Image credit Anna Müeller

Similarly, the complex multilevel freeway that bisects the entire urban renewal project site, is a pivotal piece of existing infrastructure that requires careful urban design consideration. This structure proved an exceedingly difficult modelling challenge, with little available data to inform the process. In addition, as we had selected a 2.5D visualisation method, this complex structure had to be interpolated to fit within an abstract 2D plane (refer **Figure *6*** and **Figure *7***).

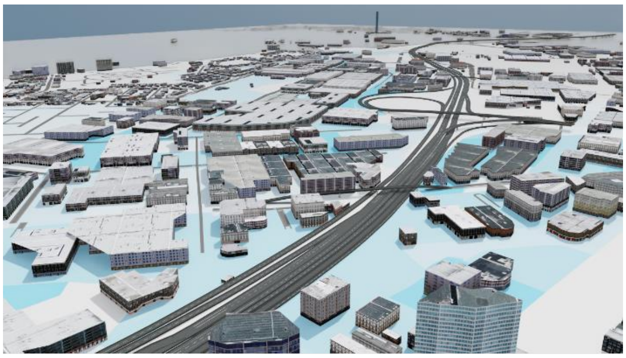

Figure 6: Shows the 3D freeway and buildings visualised over the flood extent and depth data. Image credit Anna Müeller

1.8 Developing a decision making analytic and a user interface

Our final task was to develop a prototype decision-support tool that used both the streetscape data and the flood modelling data. This analytic tool calculated the water detention capacity of both existing and proposed streets, coupled with a sub-catchment capacity analysis produced by the integrated water specialists. The intention of the analytic was to output the stormwater storage deficit between the volume capacity of the sub-catchment and the storage available in new and existing streets modified to include storm water detention infrastructure.

Figure 7: Showing the freeway and textured buildings adjacent flood depth and extent data. Image credit Anna Müeller

Furthermore, a user interface (UI) was developed to allow users to experiment with different scenarios and observe the outcomes in real-time. Given the cloud computation requirements, the scenario builder is focused on urban setting modifications (e.g., road network change). The user can propose new roads in each or several sub-catchments and the system automatically creates a database to use the sub-catchment spatial information and calculate the roads’ “*water storage*” attribute. Moreover, the system creates different road segments based on the road’s intersection with different sub-catchments. This is called splitting the proposed road by the sub-catchment area process, which allows the users to investigate the information of each segment in the road data-base and create a report on potential water storage implications of proposed road networks. Noteworthy, the UI allows users to modify the road parameters including road type and road width (refer **Figure *8***).

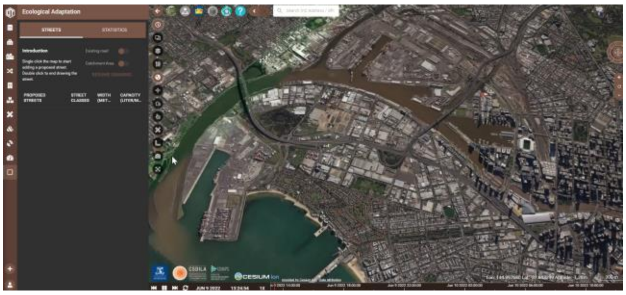

Figure 8: The user interface and flood infrastructure analytic tool prototype. Image credit Yibo Zhang

1.9 Discussion and conclusion

Here we discussed a multidisciplinary, multi-step method for adapting existing and proposed urban data into a prototype decision-support tool for strategic planning and urban design decision-support, with a real-time analytic within a DT environment. We found the following:

- That a spatially enabled Digital Twin Platform was adaptable to the needs of strategic planning decision-making for flood infrastructure in urban renewal.
- That GIS data and models such as sub-catchment modelling and flood extent, and BIM models such as freeways and proposed buildings could be integrated into the framework, though, substantial reformatting and simplification of each was required. The design of the data simplification was intrinsically dependant on the purpose of the tool.

- That visualisation methods used in the DT, required discipline agnostic re-labelling and reformatting of data. This need should inform future data collection, maintenance and storage processes, toward development of a standard, straightforward but flexible framework, adoptable by industry and the public sector alike for data and model records.

Stormwater flooding is a particularly challenging aspect to work with in digital environments as ground surface data is handled in a multitude of ways in digital globes and hydrological modelling software. These discrepancies, and issues associated with autogenerated surfaces, particularly in areas such as those under complex multilevel freeways and bridge structures, can result in substantial issues for both visual and analytic outputs.

Complex geometry

DTs that include analytics and visualisation and are concerned with the interface between 3D topographic surfaces; the ground, streets, parks, with building ingress and egress, present a particularly difficult challenge. First, the 'ground', and particularly streetscapes with fine-scale water management detail such as drains and kerbs, represent notoriously complicated geometry. Second, there is often no set boundary to a site intervention, merely a 'fuzzy' edge between changing and unchanging aspects of the ground plane. Third, sites often contain complex 3D infrastructures such as multilevel freeways, overpasses, bridges, and tunnels that are poorly handled by autogenerated techniques available in digital globes such as Cesium Ion ™.

Addressing these complexities requires an appraisal of BIM construction methods: Specifically, we found we could not utilise the aerial photography applied over the autogenerated terrain. Instead, we developed a modelling approach to the freeway and overpasses, that allowed it to 'sit' as a 3D BIM object over the top of underlying 2D data. This required extensive manual analysis to ascertain the boundaries of the 3D freeway objects, and for this to be modelled in external proprietary software, and imported into the DT. We also found the aerial imagery was unsuitable for visualising the road network as the bridge and overpass structures were mapped to the ground plane. To alleviate this problem, we used ESRIs City Engine, rule-based road generation software to generate a visually compelling road network, based on the edited transport road centreline data set (buffer by width technique). The visualisation result was thus 'semi abstract', which allowed greater visual clarity between elements. However, both external propriety software platforms used for the road network and freeway model required extensive skills to operate and some issues such as georeferencing, ground and position anchoring and material display were complicated to control.

Real-time analytics

Real-time analytics are critical for increasing situational awareness and timely decision-making. The reliability, scalability and performance of real-time analytics are the challenges for handling city-scale real-time information from multiple sources. The capabilities for "looking-back" and "looking-forward" are also required for city performance assessment and prediction. While flood modelling can be used for design-decision making, the level of accuracy is not required to meet standards of accurate risk assessment. This can be difficult to explain in layperson terms as any analytic will 'appear' to output 'exact' numbers. In the future, it will be necessary to develop ways to 'wrap' exact numeric data with 'softer' more descriptive terminology within the module interface.

Coupling modules for urban design decision support to existing DT infrastructure could alleviate some of these issues. For Digital Twins to be attractive to designers, they must offer decision-support, design analytics and evidence-based outcomes both at speed (real time) and within workshop environments. The lack of uptake of DSS in the design and planning industries is often attributed to cost, as digital scenario modelling techniques, are time-consuming, require a high degree of skill and are often polygon dense, needing both intensive computing power and expensive software to process. In addition, discipline-specific modelling such as hydrological modelling, can require considerable reformatting, re-interpreting, or reconfiguring to make them accessible, and interoperable with data and modelling from the myriad of other discipline-specific considerations; transport networks, housing, and land use, and living, environmental systems such as climate and solar exposure.

Implications for future design methods

To truly leverage the potential benefits of Digital Twins, the decision-making methods of design disciplines need substantial change. New experimental workflows that test issues of interoperability, for example, integration of BIM models from various platforms, development of working methods that allow complex geometry to interface with autogenerated DEM terrains, and integration of data from disciplines such as integrated water management, where outputs may need lay-person interpretation within a DT environment are desperately needed.

Using data generated for one discipline's purpose to answer the questions of another discipline

Simulating and predicting futures is a key feature of DTs. So, for a typical landscape design project, the expectation is that we would normally have several simulation and prediction models simultaneously. In some cases, such as hydrological modelling and simulation, microclimate behaviours, and network analysis (for roads and water streams) we might consider running separate digital twins seamlessly, but connected, which creates a digital thread to answer complex and multi-disciplinary questions. As such, a research agenda for the digital thread as a mechanism for populating a data flow and communicating with different systems is essential in the future.

Thus, design of integrated stormwater infrastructure represents a complex multifaceted problem requiring clear, discipline agnostic communication techniques, tools and analytics that are easily accessible, visual, and work with data for many different modelling priorities.

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