Rapid Development of A Spatial Digital Twins Using Open-source Solutions

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Abstract

City-model spatial Digital Twins are a three-dimensional virtual self-updating twin of a city which is updated by real-time data. This paper explores the effectiveness of open-source data and tools that can generate a Digital Twin to be hosted on a distributed system. A spatial Digital Twin was successfully generated from a city-model made from open-source spatial data with access to real-time data. The Digital Twin application was hosted on a three-tier systems architecture. The exception to the open-source data was a Digital Surface Model (DSM) obtained from a private source. However, the DSM was an optional component. The output only met the minimum requirements of a Digital Twin while the visualization was basic where the live data was limited to global weather data rather than city-specific data. The investigation indicated that even with little data, generating a 3D city scene with an automated live data flow meets the spatial Digital Twin's minimum requirements according to Piroumian (2023). The main contribution of the study is highlighting methods for generating and hosting a spatial Digital Twin and its associated data onto the web through using a three-tier architecture to store, host and display the Twin onto the web. The areas identified for further research include investigating variations in the distributed systems for hosting and publishing a spatial Digital Twin onto the web. A secondary subject of investigation is exploring methodologies for improving the detail of the spatial Digital Twin's data for areas that do not receive much live data.

1. Introduction

1.1 Spatial Digital Twins

Digital Twins are a reflection of real physical objects and processes represented by a simulation model generated in a digital environment (Batty, 2018). A spatial Digital Twin functions identical to a generic Digital Twin. The difference is that all objects and systems are represented in a spatial context which includes the dimensional attributes and precise location placement (Ali et al., 2023). What makes a spatial Digital Twin different from a 3D model or simulation is that it is receptive, meaning it has the ability to react to real-time data for decision making (Batty, 2018). The primary element of a spatial Digital Twin compared to a 3D model is capturing live changes from the real-world and representing it on the virtual twin. The main characteristics for building a spatial Digital Twin should consist of a physical twin, virtual twin and a channel that communicates data and information between each other (Piroumian, 2023). This means that a 3D model/twin of the area of interest will not be defined as a spatial Digital Twin until there exists a form of live data being consistently communicated between the physical object and virtual twin. Rapid foundation development of the spatial Digital Twin involves prioritising quick generation to investigate whether the spatial Digital Twin can meet the technical requirement.

The optimal data and visualisation characteristic for a spatial Digital Twin is having spatial data that can be represented in a 3D format that receives consistent updates (Schrotter and Hürzeler, 2020). For instance, the spatial Digital Twin of Zurich used sensors and cadastral information to optimise the accuracy of the features present in the city so that the information is always being updated (Schrotter and Hürzeler, 2020). An additional component of the data that is beneficial is having metadata embedded into the spatial data. Good quality spatial data that can be edited and manipulated is necessary for generating the spatial Digital Twin, and in some cases more than 60 geospatial layers have been used to create a proof-of-concept spatial Digital Twin (Duque and Brovelli, 2022). The minimum requirement for building a spatial Digital Twin requires a virtual model that can represent the physical structure of subject and the presence of live data or information that can be communicated and exchanged between the physical world to the virtual realm (Dani et al., 2023). While the optimal data requirements would be using editable spatial data and obtaining live information that comes from sensors in the area of interest, this aspect is dependent on whether the physical area has these sensors installed and whether the sensor data is open-source.

1.2 Open-source data and tools for generating and hosting a spatial Digital Twin

This study investigates the technical requirements and resources needed to generate a spatial Digital Twin hosted on the web. The Digital Twin's data and display is important, but it is also crucial to have a method to host and publish the Digital Twin as a functioning application. The evolution of Web 3.0 technologies transforms users from passive clients to generating and uploading their own content (Wang et al., 2023). The ability for users to develop their own content and participate in an online environment has led to the development of online communities dedicated to creating open-source tools and data. These open platforms and resources can lead to frameworks and web applications that are entirely derived from user-generated content. The open-source data, data that can be obtained, accessed, modified and used by anyone, provides spatial data to generate the spatial Digital Twin. What constitutes as open-data and tools includes all associated spatial data, software implemented and access to the live data and APIs used. The tools provide the means to store, host and publish the Digital Twin as a web application through a distributed system. Open-source tools that are used as spatial applications are Cesium for generating and sharing 3D geospatial data and Mapbox to create and share maps onto the web.

1.3 Research objectives

The following research objectives have been defined below:

- Explore the availability of open-sourced spatial data of area of interest and check its suitability for generating Digital Twins. This would require the generation of a 3D model of the urban area using open-source tools and plug-ins, and subsequently linking real-time information from the physical world.
- Export the generated Digital Twin onto the internet as a functional web mapping application to be hosted onto the web as a distributed system using a three-tier architecture. This requires finding a database to store the data, a server so that the data can be shared onto the web and developing a front-end presentation so that the information can be displayed as a web application.

2. Proposed Methodology

2.1 Case Study

For the case study, we choose the City of Honiara, Solomon Islands. Honiara is the capital city of the Solomon Islands, being the largest city of the Solomon Islands and located on the north-western coast of Guadalcanal. Honiara was chosen as the study area for this investigation as Honiara has had few spatial analysis-related studies on the city. The only spatial analysis that has been performed for Honiara being health related and natural disaster-based investigations using only 2D data. This study aims to generate a spatial Digital Twin using the available open data of Honiara from an urban planning perspective. This is because Honiara is measured to have one of the highest urban growth rates at 4% per year (Parker, 2010), leading to the increasing occurrences of informal settlements by the lower and middle-class citizens (Foukona, 2015).

These occurrences of informal settlements are causing confusion to the official owners of individual buildings within Honiara and is an example of ongoing urban planning issue. This situation provides an opportunity to showcase the benefits of using a spatial Digital Twin of Honiara that can mitigate the ownership issue. A spatial Digital Twin can address this issue by providing real-time urban analytics such as population growth, information of official buildings and current ownership and residents of houses and property. This can help the local government investigate which buildings are legally built by displaying building history information and which are informal and illegal settlements. Another function is that the spatial Digital Twin can compare the number of official tenants and owner of a living space to who has been physically sighted and living on the premises.

A detailed spatial Digital Twin can address the health and vulnerability issues and support the investigations occurring within Honiara. Household data was stored on spatial databases with georeferencing for malaria cases recorded where the data was obtained by physical cards distributed and collected by volunteers (Kelly et al., 2010). A distributed systems architecture can improve this system by generating an application that stores the household information onto a back-end database and can be edited by the household owners at any given time. The effectiveness of evacuation facilities would benefit from the spatial Digital Twin’s dynamic data. It was discussed that the facilities can be overcrowded while others were not used (Reuben and Lowry, 2016). The spatial Digital Twin can provide live data of which facilities are recommended for households to travel to based on their current location and which ones are currently at full capacity.

The health vulnerability study of Honiara (Natuzzi et al., 2016) and malaria study (Kelly et al., 2013) can benefit from both the three-tiered architecture and the spatial Digital Twin’s capabilities. The application can allow citizens to provide volunteered geographic information (VGI) to update any new malaria case occurrences along with associated side-effects that have been occurring from the diseases. The distributed systems allow back-end developers to update the databases to support more information based on user feedback and information. The spatial Digital Twin’s self-updating capability can predict if another health-incident from an extreme weather event would occur. This is by comparing the past weather event’s conditions to the forecasted future conditions to identify similarities and probability of the same event occurring. The spatial Digital Twin can also map the areas most affected based on the information it receives along with assess vulnerability in real-time based on the current conditions and associated vulnerability indicators. This front-end application that enables user input can help spread awareness on the on the current vulnerability of the population.

2.2 Methodological Framework: Three-tier architecture

The methodological framework was developed from a three-tier architecture of a distributed system: the data-tier, application-tier and presentation tier (Luaces et al., 2005). The data-tier involved gathering and processing the data to all be stored into a spatial database. The application-tier involved using a server to host the database information to be stored onto the web and connect the city-model to real-time information. The presentation-tier is publishing the information to the end-users as a web application. A three-tier architecture was used as it allows for interoperability between the tiers for development and for the user-interface (Agrawal and Gupta, 2020). This allows seamless exchange of information, enabling the application to work on an internet browser without the need of external software.

The methodological framework of generating the Digital Twin was split into the four main steps which were done in the following order from collecting the data available to releasing the front-end application:

1. Obtaining data of the study area from open-data sources.
2. Editing the data for interoperability on the 3D scene.
3. Configuring a server host and associated API installation.
4. Configuring a front-end application to host the data.

The methodological framework demonstrates hosting a potential spatial Digital Twin on a three-tiered systems architecture over generating a highly detailed spatial Digital Twin. This approach explores the capabilities and potential of operating a spatial Digital Twin on the web as an application using open-source tools. Furthermore, this open-source approach of prioritizing distributed systems investigates how effectively the average individual can generate their own spatial Digital Twins application as user-generated content rather than from an organization or entity that uses specialised programs exclusive to private companies or require a fee to use. Figure 1 demonstrates the methodological framework that was used to generate the spatial Digital Twin application from data gathering to the front-end application.

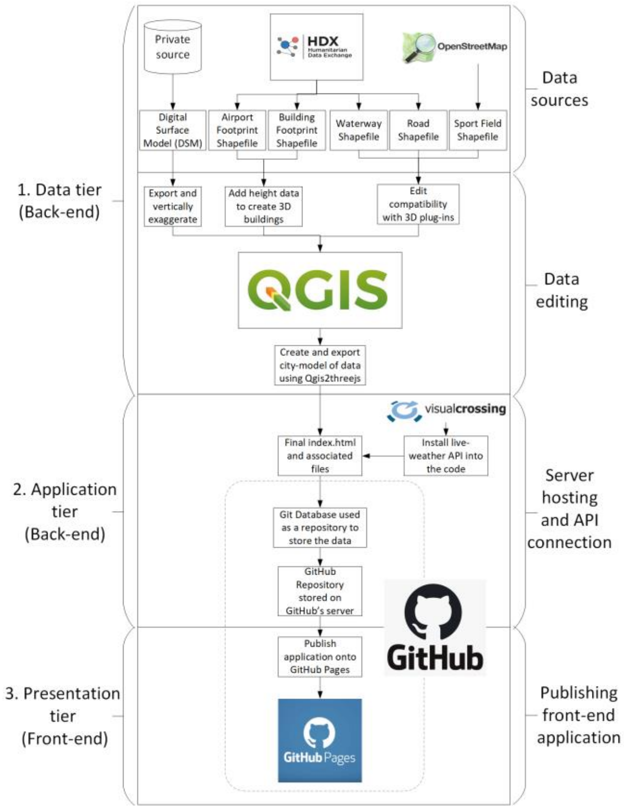


Figure 1: Framework for generating the spatial Digital Twin.

2.3 Back-end Component I: Data gathering

The back-end component of a distributed system is where data is managed, edited, added or deleted by the user (Sutanta et al., 2021). The tiers that are considered the back-end component is the date-tier of gathering data from sources and editing the data, and the application tier of server hosting and API connection.

The data collected were from open-source websites and all vector-based spatial data. Except for a Digital Surface Model (DSM) raster file of Honiara, all the other data was downloaded from open-source websites. The DSM was obtained from an external entity who has conducted a survey of Honiara. The sources used to obtain open-source spatial data of Honiara was the QuickOSM plug-in from QGIS and the Humanitarian Data Exchange website. The data downloaded from the Humanitarian Data Exchange was Honiara-based data which all consisted of shapefiles or line datasets. The line datasets obtained were roads and waterways and the shapefiles were building-based data which consisted of an airport and all other buildings present within the Honiara (Hotosm, 2022). The sports field shapefile was obtained from QuickOSM (Quickosm, n.d.).

2.4 Back-end Component II: Data editing

QGIS is an open-source tool used to edit the spatial data. The building shapefile contained the footprint outline but no height values. The data was edited to create a 3D city-model as none of the shapefile data would allow for 3D visualisation. The projection for all datasets was changed to WGS84 while the zone was changed to Honiara's: UTM Zone 57S. The building-based shapefiles of the sport field, airport and city building data were edited in QGIS where a new field was created in their attribute table. Height data was not provided on the default data and there was none available online as an open-source dataset. A placeholder numerical value was applied to this new 'z-value' field in the building-based shapefiles to allow a vertical exaggeration to be applied in the QGIS plug-in Qgis2threejs. This value was so the Qgis2threejs has a numerical value to base its vertical height on so that all buildings can appear on the 3D scene. 2D objects like the line datasets only had their projection and zone changed to keep consistent with the raster layer. There was the potential of using point cloud data to create height accurate building shapefiles which was ultimately not used. This was because unlike the DSM which was more of an aesthetic choice, the building footprints is a required component of the 3D model. A required component not being open-source meant that it will go against the main strength of the application's purpose.

2.5 Back-end Component III: Data editing for generating the 3D city model

The free-to-use plug-in Qgis2threejs was used to generate the 3D generation. Qgis2threejs uses the JavaScript-based three.js library to showcase vector data and digital models such as a Digital Elevation Model (DEM). Three.js is an open-source JavaScript library that is used for creating and displaying data as 3D models. An advantage of Three.js is its ability to integrate its display with all web browsers that support webGL, high customisation and non-proprietary license (Nishanbaev et al., 2021). These advantages enable the spatial Digital Twin's output to be displayed on any webGL-based browser, offering high interoperability for end-users. The non-proprietary license indicates that Three.js is a valuable JavaScript library for this study as it is a highly customisable open-source tool for generating the 3D city-model.

In the Qgis2threejs plug-in, all the datasets of the vector data and raster data was opened in the Qgis2threejs exporter to preview what the shapefiles looked like as a 3D model. As the default data view caused everything to appear as a flat plane, modifications were applied to generate the 3D scene. The DSM and all building data had vertical exaggeration applied to it so that the DSM's changes in elevation in the terrain can be better identified. The building data needed the vertical exaggeration to make the buildings appear more clearly as structures present on the surface of Honiara rather than 2D squares on a surface. Figure 2 demonstrates the Qgis2threejs exporter used to convert the 2D data into a 3D city model.

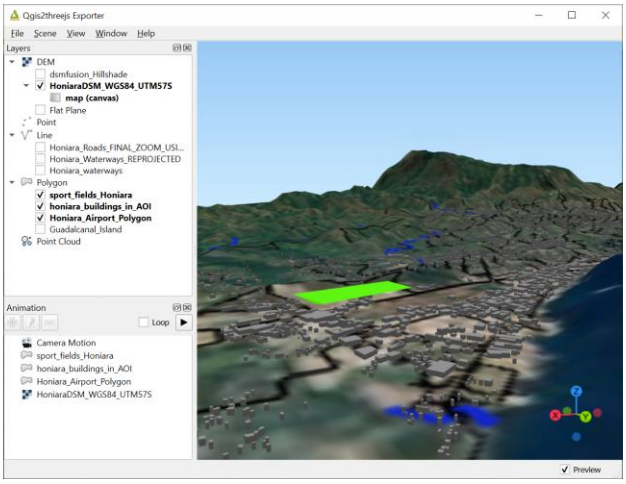


Figure 2: Qgis2threejs exporter used to preview the 3D model.

The DSM was used to visualise the elevation of Honiara on a 3D plane. Applying vertical exaggeration to the DSM was to better visualise the 3D aspect of the model. The shapefile and line datasets were added to provide detail to the 3D city model. The waterway and road line datasets were arranged so that they lay flat on the DSM as physical objects that are found on the surface itself rather than protruding like the buildings. The 3D building footprint shapefiles were arranged so that the bottom of the shapefiles are placed on the DSM itself to best simulate buildings on the surface of the area of interest. The buildings used the added attribute field as the z-value so that the Qgis2threejs exporter has numerical data to use as the height of the buildings.

After all the datasets were added onto the layout, the combined data was exported as files so that the 3D city-model could be stored and shared. The export was done through Qgis2threejs which has the ability to export the city-model as files that can be edited with controls to view the 3D generation. The city-model was generated into an HTML file with associated JavaScript and CSS files that can properly display the model as an application. The application had pre-installed controls such as the ability to zoom in and out and rotate the model.

2.6 Back-end component IV: API connection

An API connection was installed onto the HTML code so that a form of live data could be installed onto the city-model. This was so the city-model obtains a channel of real-time data from the physical-world to the virtual twin. Visual Crossing was the source of the REST API used to obtain live weather data of Honiara (Visualcrossing, 2019). An API key was obtained from Visual Crossing which is an open-source code that provides weather APIs and templates for displaying the data. As the Qgis2threejs output generated HTML code for the city-model, the REST API was installed by editing the HTML code and implementing the API key obtained. The size of the box was altered to display the next seven days as increasing or decreasing the box length would display more days or less days.

2.7 Back-end Component V: Database and server hosting

The database component used a GitHub repository to store all the associated data and files for the spatial Digital Twin. The online repository may not count as a traditional database, but it manages to act as a means to store all the data of the spatial Digital Twin. The application tier used to host the data onto the cloud was a GitHub repository. The repository may act as both the server and database but the repository itself is where the data is stored. GitHub’s servers for holding the repository is what is considered the application tier. An online repository was implemented as a significant strength is allowing permitted users who wish to access and edit the data to do so on the cloud. This offers an advantage by storing the data onto an online repository and another source rather than the database and associated files being stored on a host machine’s storage.

2.8 Front-end component: Presentation Tier

The front-end interface are web pages or components prepared for the end-user or “guest” of the application (Sutanta et al., 2021). In the framework, this is the presentation tier which is all components related to how the application can be used and how the information is presented to the end-user. The spatial Digital Twin’s front-end interface was hosted using GitHub Pages as its presentation tier to display the web application. This is because the back-end database and server were hosted on a GitHub repository which can display the HTML, CSS and JS data through the index.html file created from the Qgis2threejs plug-in.

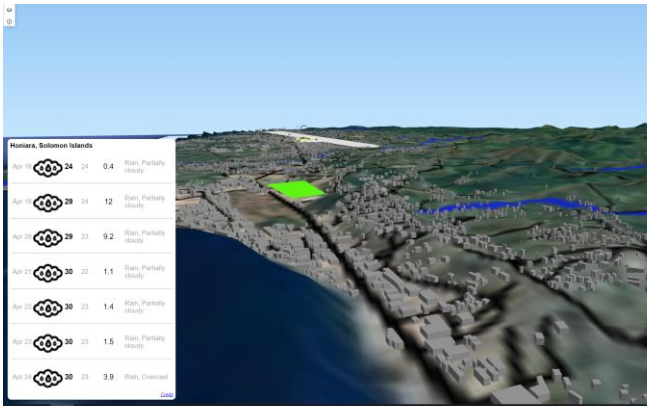
3. Discussion of Results

The web-based application generated was a basic rapidly developed spatial Digital Twin of Honiara. The application was hosted using GitHub technologies where a GitHub repository acted as the data-tier database. The repository hosted on GitHub’s servers was the application-tier while GitHub pages was used to publish the front-end web application. What was generated as the end-product was a city-model of Honiara that contained building polygons, waterway and road features, sport fields and the airport placed onto a DSM. The city-model spatial Digital Twin had a weather API installed onto the code.

A live demo of the application can be found in the link below:
https://nicholaslee264.github.io/HoniaraDT2024/

The code used to generate the spatial Digital Twin can be found in the link to the repository below:
https://github.com/nicholaslee264/HoniaraDT2024

Figure 3 depicts the front-end interface of the spatial Digital Twin application with the REST API installed. The REST API displays live weather data and forecast for the next seven days. The API can display maximum and minimum temperature forecasts in degrees Celsius, precipitation (mm) and predicted weather conditions. The DSM was overlayed with satellite imagery accessed through QGIS using Google Earth Satellite imagery from the XYZ Tiles. This was to add more detail to the basic spatial Digital Twin interface.



Honiara, Solomon Islands

Apr 18	🌧	24	24	0.4	Rain, Partially cloudy
Apr 19	🌧	29	24	12	Rain, Partially cloudy
Apr 20	🌧	29	23	9.2	Rain, Partially cloudy
Apr 21	🌧	30	22	1.1	Rain, Partially cloudy
Apr 22	🌧	30	23	1.4	Rain, Partially cloudy
Apr 23	🌧	30	23	1.5	Rain, Partially cloudy
Apr 24	🌧	30	23	3.9	Rain, Overcast

Figure 3: Front-end spatial Digital Twin interface.

The DSM used conflicted with the study’s subject and interface. The DSM was not open-source and was obtained from an external entity. This was not critical because the DSM was not a compulsory component and was used to provide more detail. The interface issues it caused was that buildings were “merged” or floating above the surface of the DSM. This may be a flaw with either the Qgis2threejs plug-in, the DSM itself or the vertical exaggeration applied to the DSM. Qgis2threejs has had better placement of the buildings on a flat surface compared to an uneven surface. Figure 4 where the placement has caused issues on the DSM. The DSM was gathered using LIDAR data. A potential solution to alleviate this problem is deriving the height of the buildings from the DSM by subtracting data from a Digital Terrain Model (DTM) if one was available.

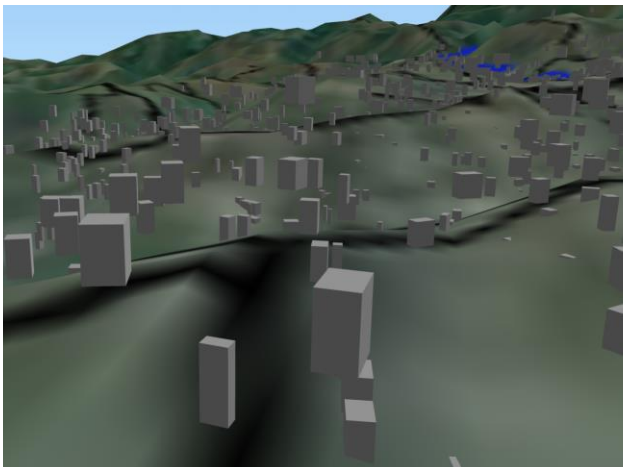


Figure 4: Issue with floating and merged buildings that occurred.

The placement of the building footprints is inaccurate and sometimes do not match up with the shape and placement of the satellite imagery. The footprint shapes are relatively accurate but their placement varied from being misplaced to not matching up at all with any buildings in the imagery. There were cases where the building footprints did not match up at all to the imagery while some buildings were missing footprints. Figure 5 demonstrates buildings that are inaccurately placed along with missing footprints.

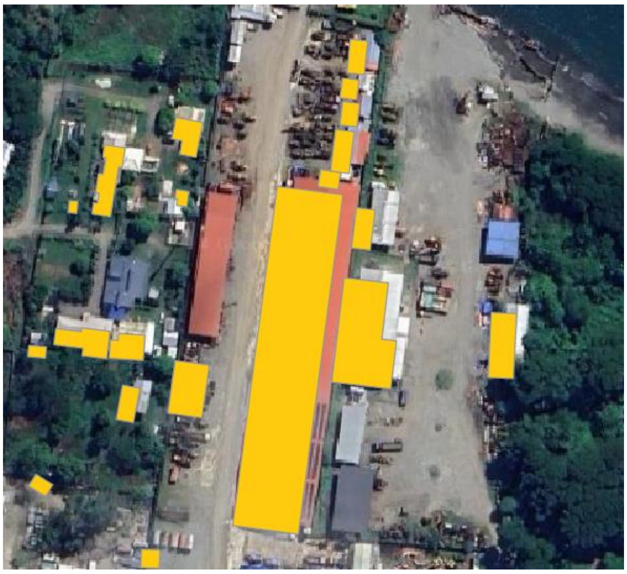


Figure 5: Placement inaccuracy of the building footprint shapefiles used to create the spatial Digital Twin.

The building shapefiles did not contain height data in the metadata. To solve this issue, a placeholder value was given to all building footprints so that they could be generated in 3D. The only source with height values for the building footprints was Cesium ion Stories. However, Cesium ion stories gave all buildings the same height value of 3, an example being rural structures being given the same height as the airport. Figure 6 demonstrates the inaccuracy with the height and placement of the buildings. The top image in Figure 6 has Honiara’s airport terminal’s estimated height measured as 3. This value was given to all other buildings in Honiara in Cesium ion stories, including structures in rural areas in the bottom image of Figure 6.

136866059

elementType	way
elementId	136866059
cesium#estimatedHeight	3
cesium#longitude	160.04582
cesium#latitude	-9.42758
aeroway	terminal
building	yes
source	Bing

747484429

elementType	way
elementId	747484429
cesium#estimatedHeight	3
cesium#longitude	160.05145
cesium#latitude	-9.43596
building	yes

Figure 6: Comparison of building height data between an airport and rural building (Cesium, 2024).

4. Conclusions

The spatial Digital Twin was generated using open-source tools and hosted as a web application on a distributed system. It relies on a basic model of Honiara city. It used building footprint shapefiles which lacked detail such as an overlay of aerial imagery for visual presentation or a higher level of detail (LOD) such as rooftop shapes. However, this was not the focus of this research. The focus was a user-generated spatial Digital Twin as proof-of-concept that could be built with open-source data and tools and be hosted as a web application through a distributed system.

A virtual 3D model representing Honiara obtains live data being communicated between the physical world to the virtual twin. The only information channel is through a global weather API. This is because unlike the Zurich Digital Twin which utilizes live sensors found throughout the city (Schrotter and Hürzeler, 2020), Honiara has little to no live data obtained from the city aside from basic data such as weather which was implemented through an API. The Visual Crossing API worked to provide updated weather data but the study area being Honiara affected the frequency it would update. The documentation on the website states that the update frequency is different between regions. North America will update on an hourly basis, Europe every three hours while the rest of the world will update every six hours.

One of the main benefits of the proposed methodological framework is an online repository hosted on a cloud server that could connect to a front-end application. The 3-tier architecture is also available to other potential users to explore other regions or replicate the methodology and tools used to create their own spatial Digital Twin.

The limitation of the study was the availability of spatial data to create a robust spatial Digital Twin. The spatial data available in Honiara affected the front-end interface and accuracy of the data displayed. For example, there were no height values in the building data and the only source with height data all used the same value.

Future research work will focus on improving a spatial Digital Twin’s foundation and concepts through open-source solutions. This can advance the robustness of spatial Digital Twins representing areas that are scarce of spatial data and the interfaces used to distribute and display the spatial Digital Twins as a web application.

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