Simulating Weather Events on a Real-World Map using Unity 3D

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Abstract: During the past decade, 3D simulation models have gained importance in the development of software solutions that aim to mimic real-world events and phenomena with increasing levels of accuracy and detail. In this paper, we introduce VOWES, a Virtual Outdoor Weather Event Simulator to replicate and measure outdoor weather events in vivid 3D visualizations. We make use of the Unity 3D engine to build the simulator environment and its virtual sensors, and integrate the Mapbox SDK and the WeatherStack API for realistic real-world weather mapping. We have conducted a large battery of experiments involving 30 human testers, considering various evaluation criteria. Results highlight VOWES' quality and performance, and its ability to simulate complex weather environments with large numbers of sensors and weather phenomena.

1 INTRODUCTION

With the rising interest in creating realistic and vivid simulations, 3D models have been gaining increasing importance in the development of software solutions that aim to mimic real-world events and phenomena. Simulation modelling allows creating and analysing the behaviour of a digital prototype system representing a physical real-world entity, aiming to study and predict the latter's behaviour and performance in the real-world (Garcia-Dorado I. *et al.* 2017). Simulation software has become one of the most commonly used techniques for virtual demonstrations in different fields, especially 3D models used to simulate real-world structures, objects, and events, with increasing levels of accuracy and detail, e.g., (Li X. *et al.* 2019, Zigon B. *et al.* 2018, Garcia-Dorado I. *et al.* 2017).

In this paper, we introduce VOWES, a Virtual Outdoor Weather Event Simulator to represent outdoor weather events and data in vivid 3D visualizations. It is designed as a digital twin solution to describe and replicate weather measurements, events, sensors, and their properties from the real-world, into a software simulation environment. We make use of the Unity 3D engine to build and design the simulator environment and its virtual sensors. We develop special visualizations and behaviours to present weather measurements, events, and sensors as visible 3D structures with specifications controllable by the user. We utilize the Mapbox SDK (MapBox 2021) to import high-resolution world maps showing countries, cities, and buildings. In addition, we utilize the WeatherStack API (WeatherStack 2021) to capture real-time weather measurements and conditions from the geographic area that is being simulated and integrate them in the simulation environment to allow for more realistic and accurate simulations. Qualitative and performance evaluations highlight the potential of the tool.

In the following, Section 2 reviews related works. Section 3 describes the VOWES simulation tool. Section 4 describes the experimental evaluation, before concluding in Section 5 with future directions.

2 RELATED WORKS

With the rising interest in creating realistic and vivid models, Unity 3D has been gaining increasing importance as a powerful tool for the creation of 3D visualizations, functions, and attributes, and their integration with dedicated processing features and metric measurements to achieve accurate outputs and analyses. Unity is a cross-platform game engine developed by Unity Technologies, which was

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announced and released in June 2005 at Apple Inc.'s Worldwide Developers Conference as a Mac OS X-exclusive game engine. Starting in 2018, the engine has been extended to support more than 25 platforms for creating two-dimensional (2D), three-dimensional (3D), augmented reality, and virtual reality games. Also, the Unity engine has been used for simulations in various fields including architecture, engineering, automotive, and construction, e.g., (Sanders B. *et al.* 2020, Sun L. *et al.* 2020, Wang R. *et al.* 2020). One of its distinctive features is the power of its real-time 3D rendering, making it one of the world's leading real-time development platforms (Unity).

In this context, several Unity 3D-based simulation solutions have been developed in the literature. In (Wazir H. and Annaz F. 2015), the authors design a Unity-3D simulator to help navigate unmanned aerial vehicles (UAVs). The latter is coupled with sensors and physical hardware allowing to collect data from the UAV's surrounding environment and feeding it into the virtual simulation for processing and analysis. The authors emphasize the importance of Unity 3D in presenting a realistic and precise model while tracing the performance of UAVs in the real-world. In (Buyuksalih I. *et al.* 2017), the authors develop a Unity 3D virtual environment to study the properties and potential prospects of using solar energy on buildings in a highly populated urban area. They mimic building structured using dedicated 3D visualizations, and mimic solar energy measurements based on values and calculations accumulated from a real world urban area in the city of Istanbul. The authors specifically address the challenge of attaining high accuracy in predicting solar energy outcomes with the influence of the buildings' shadow casting. The authors extend their simulated environment to represent and study the underground utility systems in the city, where the whole city map is translated into a dedicated underground 3D model. In (Jain V. and Mahdavi A. 2016), the authors design and integrate virtual sensors to measure light conditions in both indoor and outdoor environments. They focus on monitoring daylight conditions and design artificial light sources to map different sunlight conditions in the real world. They accumulate measurements from real sensors and map the data to the virtual sensors to create realistic conditions in the virtual environment. The authors utilize dedicated CAD software to create both indoor and outdoor environments with high degrees of precision and accuracy. Unity 3D is used to animate the CAD environment and handle light condition variations and sensor simulations. In (Wazir H. and Annaz F. 2015), the authors show how environmental events, such as fire, can be demonstrated in a 3D manner. They attempt to imitate real-life scenarios and study the level of stress that different people might face in simulating different kinds of fire events. The authors highlight the capabilities of Unity 3D in visualizing and animating complex objects and events such as *fire*, *flame*, *smoke*, and their propagation.

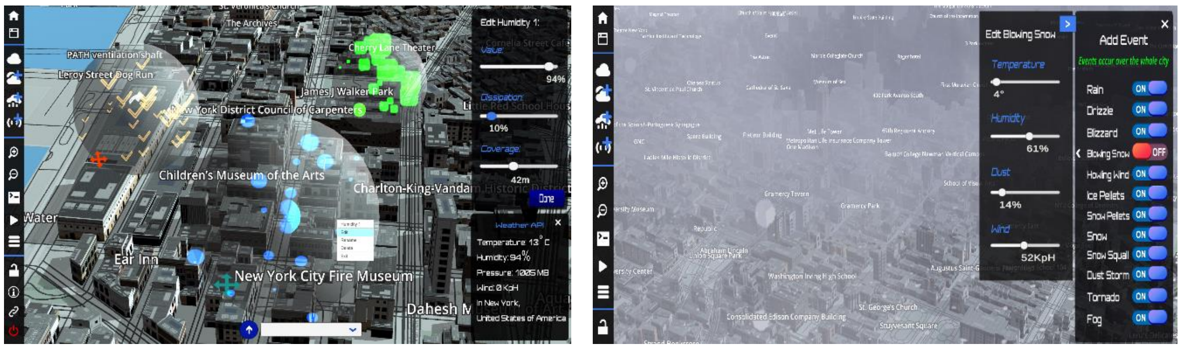
3 VOWES SIMULATION TOOL

We design and develop our VOWES simulation tool using the Unity 3D game engine to build the environment and its virtual sensors, and integrate them with real-world 3D maps and a weather API for realistic weather mapping. We develop special visualizations and behaviours to present weather measurements, events, and sensors as visible 3D structures with specifications controllable by the user. The following subsections describe the main components of our simulator tool.

3.1 Virtual 3D World

To achieve a realistic 3D simulation of outdoor environmental events and measurements, we use Unity's flexibility in integrating third-party APIs to acquire dynamic 3D maps and real-world weather measurements. More specifically we utilize the Mapbox SDK (MapBox 2021) to import high-resolution world maps showing countries, cities, and buildings, and we integrate the WeatherStack API (WeatherStack 2021) to capture real-time weather measurements and conditions from the geographic area that is being simulated.

Mapbox offers APIs, SDKs, and live-updating map data, allowing to build better mapping, navigation, and search experiences across different platforms (MapBox 2021). We utilize the Mapbox SDK to import the 3D maps of real-life cities and allow the user to explore and visualize those cities from within the Unity 3D environment, with high levels of detail, where particular locations or buildings can be easily leveraged for procedurally generating user-specific experiences or styling. Users are prompted to select their city of choice upon launching a new simulation project. Consequently, the data layers are imported and built into the Unity 3D environment, including buildings data, points of interest (POIs), roads, and real-time traffic data, where the data can be fully customized within Unity 3D's development environment (e.g., changing the layout of certain buildings, adding a building, removing or changing the properties of a road, etc., cf. Figure 1.a). In addition, we utilize the WeatherStack API (WeatherStack 2021) to acquire real-time weather data for the selected city being simulated by the user[2], while storing a 14-day historical record of the weather information. The historical record is useful to allow weather forecasting through the simulator. Following the user's selection of the city of interest, and upon launching the simulation project, the tool automatically acquires and processes the real-data weather information and presents the corresponding visualizations and behaviours on-screen (Figure 1.b).



a. 3D visualization of the city of New York, with sample weather measurements and some of their parameters

b. Sample visualization of the city of New York, shown during a snow storm in late January 2021

Figure 1. VOWES simulation tool snapshots of the city of New York

3.2 Virtual Weather Measurements and Events

We develop a dedicated weather simulation module using Unity 3D's Particle System graphics (Unity 2020) to create dynamic weather objects, visualizing and simulating the behaviours of *weather measurements* (e.g., *wind*, *humidity*, *temperature*) and *weather events* (e.g., *storm*, *tornado*, *fire*). We utilize Unity's particle system to render small images, called particles, and control their collective behaviour to produce visual effects where every particle within the system presents an individual graphical element in the effect. Every particle system is modelled as a 3D sphere object with mutable boundaries, serving as a container for a blob of particles associated with the target weather measurement or event. The object's properties can be defined and fine-tuned by the user through controllable parameters (e.g., coverage, value, dissipation) as seen in Figure 1.

3.3 Virtual Sensors and Multi-Sensors

We define a *virtual sensor* as a spherical Unity 3D game object with mutable boundaries, having user-controllable properties including *location* (coordinates of the sphere's centre point), *measurement range* (radius of the sphere), *sampling rate* (frequency of capture), and *sampling accuracy* (precision of capture, cf. Figure 2). Every weather measurement is associated with an identifying tag, which is assigned to the corresponding virtual sensor objects once its measurable feature is chosen by the user. The user can easily toggle between the sensors' measurable features using their identifying tags. The tags help identify all virtual sensor game objects without the need for any additional manual code writing or Unity scripting. A *virtual multi-sensor* is modelled as a set of multiple overlapping 3D sphere objects where each sphere object represents an individual virtual sensor. This allows a multi-sensor to capture multiple weather measurements from its constituent virtual sensors and allows flexibility and modularity in designing different kinds of virtual sensors. The sensed values are based on the user-chosen properties for the corresponding weather measurement or the event object. Knowingly, the sensor starts first finding the contact points with the weather game object, estimating the corresponding weather value at each point, accumulating the average of all points, and showing the output values to the user through the database console. This process is done continuously until no weather item is detected within the sensing range. As soon as the collision ends, the

[2] WeatherStack API is utilized by more than 75k companies worldwide, providing multi-year history and live data (WeatherStack, 2021).

function *on collision exist* indicates that contact has been broken between the sensor and the weather game objects, signaling the end of the weather measurements sensing process.

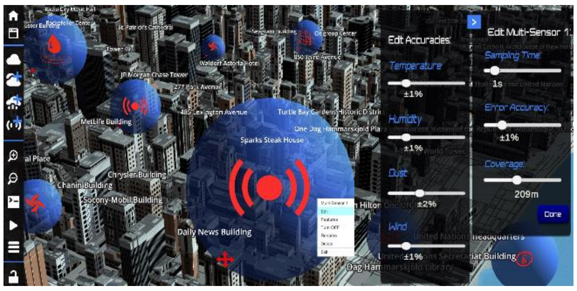
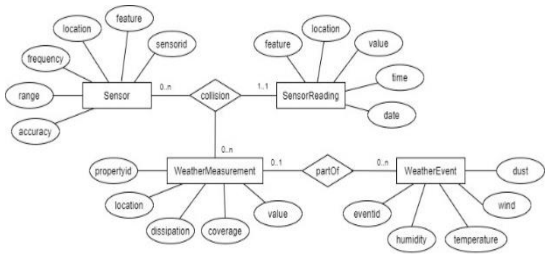
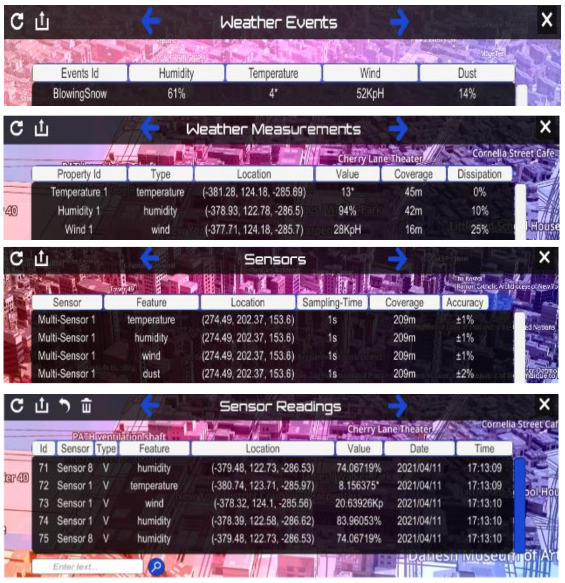


Figure 2. Virtual sensor configuration panel



a. Conceptual ER describing an extract of the database



Weather Events

Events Id	Humidity	Temperature	Wind	Dust
BlowingSnow	61%	4°	52KpH	14%

Weather Measurements

Property Id	Type	Location	Value	Coverage	Dissipation
Temperature 1	temperature	(-381.28, 124.18, -285.69)	13°	45m	0%
Humidity 1	humidity	(-378.93, 122.78, -286.5)	94%	42m	10%
Wind 1	wind	(-377.71, 124.18, -285.7)	28KpH	16m	25%

Sensors

Sensor	Feature	Location	Sampling-Time	Coverage	Accuracy
Multi-Sensor 1	temperature	(274.49, 202.37, 153.6)	1s	209m	±1%
Multi-Sensor 1	humidity	(274.49, 202.37, 153.6)	1s	209m	±1%
Multi-Sensor 1	wind	(274.49, 202.37, 153.6)	1s	209m	±1%
Multi-Sensor 1	dust	(274.49, 202.37, 153.6)	1s	209m	±2%

Sensor Readings

Id	Sensor	Type	Feature	Location	Value	Date	Time
71	Sensor 8	V	humidity	(-379.48, 122.73, -286.53)	74.06719%	2021/04/11	17:13:09
72	Sensor 1	V	temperature	(-380.74, 123.71, -285.97)	8.156375°	2021/04/11	17:13:09
73	Sensor 1	V	wind	(-378.32, 124.1, -285.56)	20.63926Kp	2021/04/11	17:13:10
74	Sensor 1	V	humidity	(-378.39, 122.58, -286.62)	83.96053%	2021/04/11	17:13:10
75	Sensor 8	V	humidity	(-379.48, 122.73, -286.53)	74.06719%	2021/04/11	17:13:10

b. Sample data produced by the VOWES simulator tool

Figure 3. Extract of the VOWES database schema and sample data.

3.4 Environment Data Storage

The data generated through the VOWES simulation environment, including virtual weather measurements and events, as well as virtual sensor properties and readings, are organized and stored in a relational database structure. Figure 3 shows the database conceptual schema and corresponding sample data snapshots from the simulator tool. The data from every simulation project is saved in the database, with its timestamp under the user's account, and can be utilized by the user to save, exit, reload, refresh and query the simulation project. The data is also essential to allow the development of data monitoring, mining, and extrapolation functionalities, including project versioning, temporal querying, measurement forecasting, and event prediction. For instance, while VOWES does not currently perform forecasting and prediction, yet it will allow visualizing predicted events once their data becomes available. In other words, VOWES will allow the user to easily fast-forward (or fast-backward) in time to visualize the weather environment and its events in the future (or in the past), according to the available temporal data in its database. The predicted events and their measurements will plug into VOWES and benefit from its visualization functionalities. The latter are outside the scope of this work and will be addressed in a future study.

4 EMPIRICAL EVALUATION

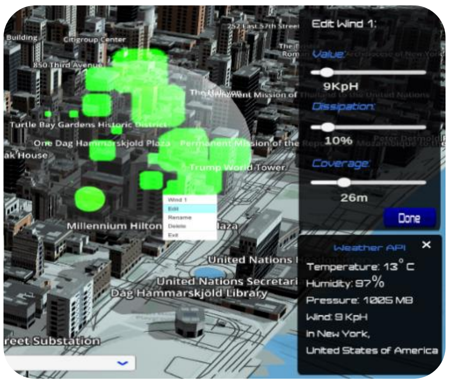
We have conducted qualitative and performance evaluations to assess the VOWES' tool, considering three evaluation criteria: i) *simulation accuracy*, ii) *user friendliness*, and iii) *time performance*. The prototype system is available online[3].

4.1 Simulation Accuracy

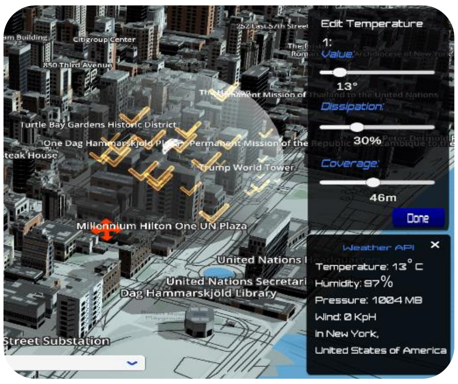
An essential feature in our simulator is the functionality of the *virtual sensor* (and *virtual multi-sensor*) component(s). As described in Section 4, a virtual sensor is designed to mimic the behaviour of a real sensor in the virtual simulation environment, by capturing weather measurements (e.g., *temperature*, *humidity*, *wind*) based on the occurring weather event. To test the accuracy of the weather measurements made by virtual sensors, we refer to the real-time weather values given by the integrated weather API,

[3] http://sigappfr.acm.org/Projects/VOWES/

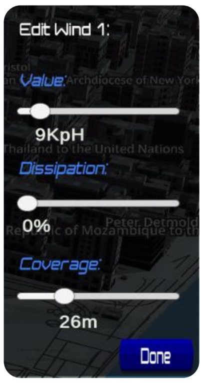
which are set as the initial values for any weather measurement or event as seen in Figure 4.a and b. The weather values provided by the weather API are regularly updated in the simulation tool, to highlight the real weather conditions in the chosen geo-location being simulated. We also test the performance of the virtual sensors by checking their readings in comparison with the selected weather measurements and their associated properties (e.g., *value*, *dissipation*, *location*, *coverage*). For example, if we select a *wind* measurement and set *dissipation* to 0% (cf. Figure 4.a), we expect the sensor to capture the same specified wind speed value returned by the API as long as it occurs within its coverage area, regardless of its collision location (cf. Figure 4.d). Yet if we set the temperature dissipation parameter to 50%, and we incrementally move the virtual sensor away from the weather measurement's location, we expect the sensor to capture temperature values at a decreasing rate of 50% considering the sensor's collision location w.r.t. the temperature measurement location (cf. Figure 4.e). We follow the above approach by modifying all the weather measurement properties and checking the virtual sensors' measurements accordingly. For every property, we consider 10 variations of equal spans (e.g., *temperature* varies between -30, -20, …, 60° Celsius, *dissipation* varies between 0, 10, 20, …, 100%). The results produced for all property variations and tests concur with the virtual sensors' expected measurements, denoting their simulation accuracy.



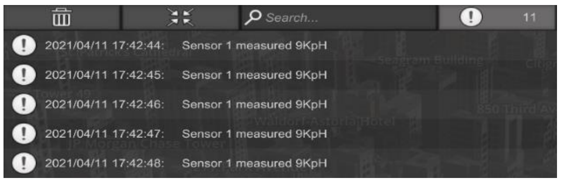
a. Sample wind measurement



b. Sample temperature measurement

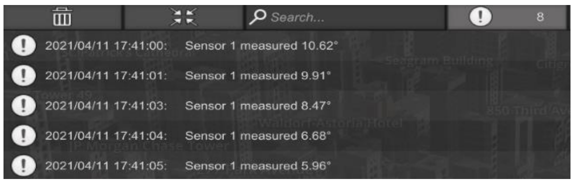


c. Parameters' panel



```
2021/04/11 17:42:44:   Sensor 1 measured 9KpH
2021/04/11 17:42:45:   Sensor 1 measured 9KpH
2021/04/11 17:42:46:   Sensor 1 measured 9KpH
2021/04/11 17:42:47:   Sensor 1 measured 9KpH
2021/04/11 17:42:48:   Sensor 1 measured 9KpH
```

d. Wind speed readings with no dissipation (cf. a)



```
2021/04/11 17:41:00:   Sensor 1 measured 10.62°
2021/04/11 17:41:01:   Sensor 1 measured 9.91°
2021/04/11 17:41:03:   Sensor 1 measured 8.47°
2021/04/11 17:41:04:   Sensor 1 measured 6.68°
2021/04/11 17:41:05:   Sensor 1 measured 5.96°
```

e. Temperature readings with 30% dissipation (cf. b)

Figure 4. Display of weather measurement properties (a b, c) and sensor readings (d, e).

4.2 User-Friendliness

The VOWES tool is designed to allow non-expert users who have no previous knowledge about the simulation tool to be able to easily utilize it and benefit from its functionalities. Hence, we evaluate the tool's user-friendliness by performing two kinds of evaluations: i) GUI[4] testing, and ii) usability testing. The former aims at checking the GUI's input fields and components, while the latter aims at checking the ease/difficulty of usage of the software tool by non-expert users.

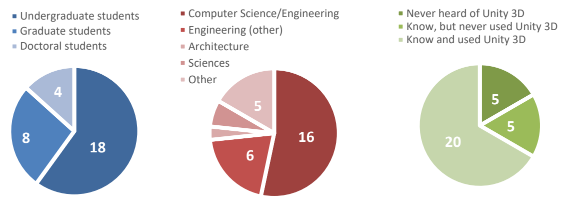
GUI Testing: In this experiment, we check the display of input fields and buttons on the screen considering the aspects of size, alignment, and content. We also check the menu and parameter panels of the application by testing their buttons and mouse hovering functionality, and their impact on the main display. This is applied on all user-interfaces in the whole simulator, starting from testing the

[4] Graphical User Interface

capability of generating more than one project simultaneously (through the main page), to the ability to select a country/city and viewing it in a 3D environment, as well as scrolling and zooming in and out of the map with high resolution and details. We also evaluate and test the ability to add weather measurements and events in the same simulation project, and we test the functionality of the designed buttons by pressing each button more than 50 times consecutively. In addition, we make sure that all the weather measurements are movable around the map, by relocating every one of them more than once. We apply the same testing on the virtual sensors, where we perform 10 consecutive addition, renaming, deletion, and movement operations on every sensor in the simulation exercise. Similarly, we test up to 10 separate projects by launching every project using a different city map, populating it with weather measurements, weather events, and virtual sensors, saving it, closing it, re-opening it, and verifying that the sensors, measurements, events, and their values and locations are correctly loaded and initialized respectively. Furthermore, we test the parameter panels associated with every visual component by checking the functionality of its buttons and range sliders (describing *coverage*, *value*, and *dissipation*, cf. Figure 4.c) and observing their impact on the visual component. Results of all GUI tests were successful and allowed fine-tuning and improving the visual aspects and behaviour in the simulation tool.

Table 1. Simulation tool usability evaluation criteria

Criterion	Description	Evaluation question
Stability	It is the ability of the software tool to function over a long period of time without crashing.	Given the criterion's description, how satisfied are you with the stability of the simulation tool?
Look and Feel	It refers to the first impression a user has after using the software tool.	Given the criterion's description, how satisfied are you with the look and feel of the simulation tool?
Ease of Use	It describes how easy and straightforward it is to use and manipulate the software tool.	Given the criterion's description, how satisfied are you with the ease of use of simulation tool?
Functionality	It refers to the capacity of the software tool to provide useful functions and features serving its main objective.	Given the criterion's description, how satisfied are you with the functionality of the simulation tool?
Responsiveness	It refers to the time it takes the software tool to execute a certain action or behaviour.	Given the criterion's description, how satisfied are you with the responsiveness and overall speed of this application?
Format	It refers to the materials and options provided (e.g., buttons, instructions) and their organization within the software tool.	Given the criterion's description, how satisfied are you with the format of this simulation tool?
Navigation	It refers to the interactions that allow users to navigate across, into, and back-out of the software's format (e.g., back to the main page, opening/closing side menus, zoom in/out).	Given the criterion's description, how satisfied are you with the navigation of this simulation tool?
Icon Intuitiveness	It reflects how easy it is to guess a button's resulting action or behaviour before a user presses it.	Given the criterion's description, how satisfied are you with the intuitiveness of the icons of this simulation tool?
User Interface	It is the means through which a user controls a software application and interacts with it.	Given the criterion's description, how satisfied are you with the interface of this simulation tool?



a. Educational level b. Field of study c. Experience with Unity 3D

Figure 5. Non-expert testers' education levels, majors, and experience with Unity 3D

Usability Testing: We also created an online survey[5] to evaluate the usability and user-friendliness of our simulation tool considering nine evaluation criteria: i) *stability*, ii) *look and feel*, iii) *ease of use*, iv) *functionality*, v) *responsiveness*, vi) *format*, vii) *navigation*, viii*)* *icon intuitiveness*, and ix) *user interface* (cf. Table 1). A total of 30 non-expert testers (undergraduate and graduate students, cf. Figure 5) were invited to contribute to the experiment, where they independently rated every evaluation criterion on an integer scale from 0 to 4 (i.e., from *highly dissatisfied* to *highly satisfied*). Tests were conducted on a network version of the tool made available through the university's computer labs, where every computer lab consists of an HP ProLiant ML350 Generation 5 (G5) Dual-Core Intel XeonTM 5000 processor with 2.66 GHz processing speed and 16 GB of RAM. A total of 170 responses were collected, with every criterion receiving 30 rating scores. Results in Figure 6 show the average rating scores and their standard deviations aggregated for every criterion. Most testers are satisfied with the tool's usability, producing an overall average rating of 3 out of 4 considering all criteria combined. Three criteria received average scores below 3: *look and feel* (2.80), *ease of use* (2.80), and *responsiveness* (2.80). Tester

[5] Available at: https://forms.gle/F6odKynC9pcvmCzq6

discussions revealed that the latter are generally due to the perceived loading time delays of certain Unity 3D components, visual effects, or animations, which probably require increased processing power. This is a common issue with most 3D rendering environments due to their high processing and memory requirements and can be improved with the usage of GPUs and other enhancements. Few testers recommended including additional features like: i) considering the impact of outside weather conditions on indoor environments (e.g., indoor heating/cooling systems), and ii) including pollution-related measurements (e.g., carbon dioxide concentration). We plan to consider the latter in a future study.

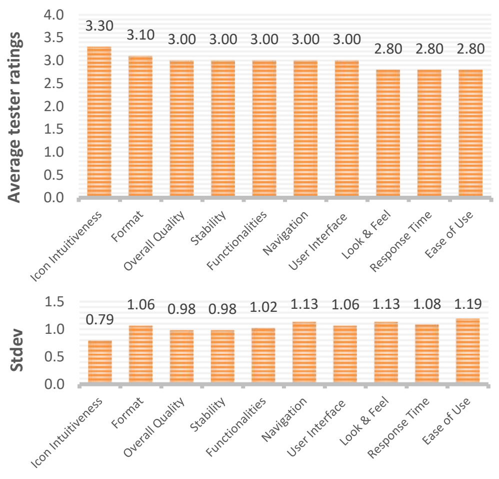


Figure 6. Average tester ratings for every usability criterion

4.3 Time Performance

The following paragraphs highlight and discuss the time results obtained during the tool's: i) setup phase and ii) simulation phase. Experiments were conducted on an HP ProLiant ML350 Generation 5 (G5) Dual-Core Intel XeonTM 5000 processor with 2.66 GHz processing speed and 16 GB of RAM.

Setup Phase: The simulation tool allows the user to visualize sensors, weather measurements (e.g., *wind*, *humidity*, *temperature*), and weather events (e.g., *storm*, *fire*, *tornado*) as objects with editable and controllable parameters. As such, we evaluate the tool's setup phase by measuring the time to create and load large numbers of game objects, ranging over: 20, 40, 60, 80, and 100 different objects where half of them represent sensors and the other half represent weather events and measurements. We start by adding 10 sensors and 10 weather phenomena with random values for their attributes. Then, we measure the time consumed to *save* and then *load* these game objects from the database, along with their respective features. Also, we measure the time to *search*, *refresh*, and *export* the game objects' data from the database, to keep track of all the sensors and weather phenomena placed or edited in a project environment. Results in Figure 7 show that most setup operations run in almost instantaneous time, where *search*, *refresh* and *export* operations share almost identical performance levels with execution time increasing by approximately 179μs for every added game object.

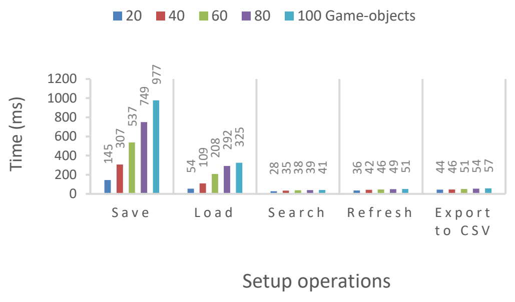


Figure 7. Execution time of setup phase operations

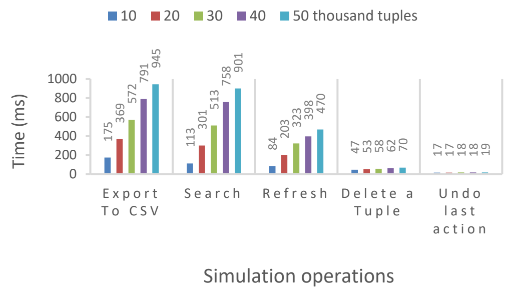


Figure 8. Execution time of simulation phase operations

Simulation phase: This phase demonstrates the sensors' behaviour in action, where sensors are detecting the weather measurements within their coverage areas, based on the features specified by the user. Each sensor works following its internal sampling rate, collecting data from the environment and storing them in the database. As a continuation of the setup phase evaluation, we create 50 sensors with a sampling rate of 0.1s (i.e., every 0.1s, all sensors carry out their reading calculations simultaneously and store the results in the database). We evaluate the time performance of sensor reading queries considering large numbers of data tuples ranging over: 10k, 20k, 30k, 40k, and 50k. We evaluate *export*, *search*, *refresh*, *delete*, and *undo* queries, by executing every query 10 times and computing the average execution time. Results in Figure 8 reflect efficient simulation time, where the maximum consumed time was detected at 945ms to *export* 50k tuples (i.e., almost 3.7MB) into an external CSV file. This highlights the tool's time performance in running large simulation projects, and its ability to simulate complex weather environments with large numbers of sensors and weather phenomena.

5 CONCLUSION

This paper introduces VOWES, a Virtual Outdoor Weather Event Simulator to replicate and measure outdoor weather events and data in 3D. We make use of the Unity 3D engine to build the simulator environment and introduce special visualizations and behaviours to present weather measurements, events, and sensors. We integrate the Mapbox SDK to import high-resolution world maps, and the WeatherStack API to capture real-time weather measurements and conditions, allowing for more realistic and accurate simulations. Empirical evaluations are promising and highlight the system's quality and potential.

We are currently extending VOWES to integrate a knowledge base structure, providing a formally description of the simulator's components (Noueihed H. *et al.* 2022). We are also investigating the impact of data collection (Moataz S. *et al.*, 2020, Ebrahimi D. *et al.* 2019, Ebrahimi D. *et al.* 2018), and data duplication and de-duplication techniques (Shazad F. *et al.* 2022, Mansour E. *et al.* 2020) on the quality and time performance of the tool. We also plan to investigate different machine learning models (Fuentes S. *et al.* 2020, Oses N. *et al.* 2020) and evolutionary developmental techniques (Salloum G. and Tekli J. 2021, Abboud R. and Tekli J. 2019), to perform weather measurement forecasting and event prediction (Hewage P. *et al.* 2021, Moreno R. *et al.* 2020). Forecasting and prediction will be added as plug-and-play layers, allowing for model transparency and extensibility.

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