Leveraging Digital Twins as Planning Support Systems for Urban Planning

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***Abstract*—Urban areas are developing rapidly and cities are getting more populated. It is predicted that this trend continues and grows rapidly in the future. Thus, it is getting more complicated to plan and manage these rapidly developing cities. On the other hand, there is also a focus on sustainability, and the United Nations has outlined sustainable development goals to be taken into account by the city planners. Sustainability is defined as a balance of economic growth, social equity, and environmental preservation. In order to overcome these challenges, making cities smart has become more popular. As a result, there are more city data available to planners and officials. Model-based planning is also getting more popular, digital twins for the cities are the new tools that use the stream of data and the models to make a digital replica of the city with a virtual representation. City digital twins have become more mainstream to help plan and manage different parts and aspects of a smart city. In this project, digital twin of Ålesund has been developed and utilized for planning the location for the construction of new infrastructures in the city. The parameters that were used for the assessment of the locations consist of, walkability, energy consumption, accessibility, and visibility. A total weighted score for each location is calculated based on the user's preferences. A case study for building a new hospital in the city has been done using the developed tool and the best location was selected based on the desired criteria.**

***Index Terms*—Smart city, digital twin, urban planning.**

I. Introduction

Urbanization is growing worldwide in both developed and developing countries. Around 68% of the world's population are estimated to live in urban areas by 2050 [1]. Therefore, it is getting harder to manage the growing urban areas; especially with regard to energy management, healthcare system, and public transportation. A city is mostly analyzed in terms of its major infrastructural assets as well as its sustainability deficit. While a city's infrastructure systems provide essential services such as water, energy, transportation, and communication to its residents, these services have a substantial effect on sustainability[2].

The United Nations' Sustainable Development Goals (SDGs) outline concerns that city authorities should emphasize as they devote resources to solving contemporary challenges. Sustainability is defined as a balance of economic growth, social equity, and environmental preservation, and it is the key to unlocking the issues that cities face. The United Nations for Smart Sustainable Cities (U4SSC) project is one of several independent smart city initiatives that have linked the SDGs to a set of 92 specific key performance indicators (KPIs) from the three main domains (figure 1)[3].

Making cities more sustainable is one of the most important challenges for humanity, and model-based city planning approaches are getting more popular and producing strong results[4]. As the trend of urbanization continues, there is a need for a new approach to administrating urban life, and hence the cities must become smarter [5]. The smart city concept has developed from controlling the city's physical growth to a broad concept comprised of physical, social, and knowledge infrastructures [6], [7]. A simplistic and narrow definition of a smart city means that city utilizes modern digital technologies to improve city services, infrastructure, and quality of citizens' lives [8]. However, a broader definition complements the socio-technical perspective and observes smart cities from economic and environmental perspectives. For instance, Caragliu, Del Bo and Nijkamp [7] consider a city is smart "when investments in human and social capital and traditional (transport) and modern ICT communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory government".

Fig. 1: Key Performance Indicators (KPIs)

With the need for smarter and data-driven solutions, more cities are transforming into smart cities. With the big data revolution, various data are available for researchers and governments to help them better manage the cities. Smarting the city is a complicated process due to the complexity of a city. The city is not an automated system that can be easily understood and predicted, but rather a living system that evolves every day through variations and developments of its physical constructs, economic and political activities, social and cultural settings, and ecological systems [9]. In order to make the city smart, a digital model of the city needs to be built. This model is based on the collected data streaming from the city and used to simulate and predict changes and visualize them; this virtual representation of the real world is called a digital twin.

The concept of a digital twin originates from Michael Grieves's 2003 presentation on product life-cycle management based on his work with John Vickers [10]. Grieves and Vicker's motivation for developing the concept were to shift from the predominantly paper-based and manual product data to a digital model of the product which would become foundational for life-cycle management. Similar concepts such as Cyber-Physical Systems (CPS) [11] and Internet of Things (IoT) [12] all focus on the idea of connecting a physical system to data collection, computation, and/or communication systems. However, approaching it from differing perspectives. In this case, the CPS concept is from the system engineering and control perspective, while the IoT concept is from the networking and IT perspective. The digital twin, on the other hand, approaches them from a computational modeling (machine learning/artificial intelligence) perspective. Nowadays with the steam of data available from the cities and also different models that have been developed to simulate different aspects of smart cities; the digital twin of smart cities is becoming more and more realistic.

The fundamental purpose of the simulation is the fact that it can realize and mitigate "unintended consequences" by developing realistic models for prediction purposes. In urban development, there is a high correlation between different systems. For example, the development of housing will subsequently cause an overburden on the native transportation infrastructure. Simulation permits planners to analyze and proactively realize cascading effects in different systems right from disaster management to energy and waste management to multi-modal transport facilities. Simulations built a vital bridge between theory and experiment [13]. Simulations driven by data points can even help in optimizing and finding solutions to long-standing shortcomings within the planning process. Generally, in long-term decision-making related to cities, humane interactions and guts play a vital role as officials gather the input of citizens through hall hearings, community planning meetings, or online interviews of citizens. This is an inaccurate decision-making approach as it is not inclusive and can be very minority opinionated. With recent technological advancements in the field of simulation as well as digital twin technology, the large amount of data can be fed to a tool to get results that can be used by urban planners in designing purposes [14][15][16][17].

Today, online data collection, sensor systems, and historical data points retrieved from the surrounding area generate an unimaginable amount of information, this, in turn, is enhancing the prediction capabilities of statistical data models. Spatial information systems, on the other hand, are becoming more and more advanced, with better analysis and visualizations which are helping in more profoundly communicating predicted outcomes to citizens thereby facilitating better decision-making. With the phenomenal growth in computing power over the last 5 years added with all the other technological growths mentioned above, urban planners can easily identify interrelationships between different systems and high complexities in smart cities [18][19][17][20]. Digital twins of smart cities can be used in various ways to help with the planning of cities. The focus of this project is finding the optimal location for the construction of new buildings in the city of Ålesund. A case study for building a new hospital has been done using the developed digital twin application.

II. Methodology

In order to develop the digital twin of a smart city, various input data need to be collected. Afterward, different models can be used for building the models and predictions, and in the end, a platform can be used to bring the models, simulations, and visualization together. The end product is an application (computer, mobile, or web) that can be utilized by planners and also citizens to leverage the digital twin in their decision-making process. In order to make the application, first the architecture of the digital twin is defined. Also, the parameters that will be taken into account are walkability, energy consumption, accessibility, and visibility. In this part, the architecture and the parameters will be explained.

A. Digital twin architecture

Different architectures for the digital twin of a smart city have been proposed in different research; based on the application and the platform. The traditional layers consist of, a data acquisition layer, data transmission layer, digital modeling and data complementary layer, data/model integration layer and application layer [21].

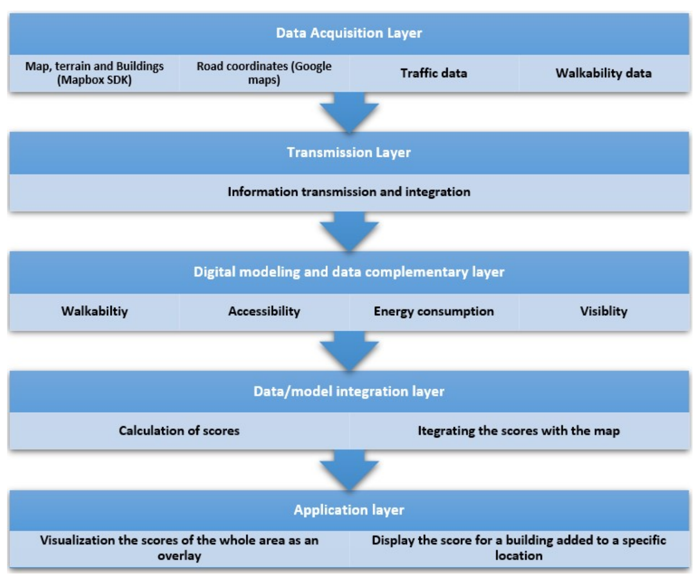

Fig. 2: Smart city digital twin architecture

1) Data acquisition layer: The data acquisition layer is the foundation of the whole app. This layer consists of various resources that provide the data required for the application. The 3D map with terrain and buildings can be provided from different resources (i.e Mapbox SDK). To visualize the various parameters on the map, geolocation data for the area is also needed.

2) Data transmission layer: After all the data were acquired, they need to be converted and transferred into the highest layers. Different means can be used for this task varying from manual data conversion to automatic data transfer using the web; depending on the data and the required processing.

3) Digital modeling and data complementary layer: The converted and processed data then will be used to make models. Machine learning algorithms can be used to make models based on the input data and the desired simulation. These models will be integrated into the application in the higher layers. So that in the final software citizen can use them to perform desired simulations.

4) Data/Model integration layer: All the previous layers will be integrated together in this layer, using the unity game engine. The map, geolocation, and models will be joined together. The scores and the calculation that has been done previously and weighted by the user are used to visualize the results on the 3D map.

5) Application layer: In this layer, the unity project is built. The application consists of parameters that the user can change to simulate, the map, and buildings. In the end, the user can use the menu to see the overlay, add buildings to different parts of the map and see the results, save the data, simulate the time and the sun, and make a decision based on these tools.

B. Assessment Parameters

Four main parameters have been taken into account for accessing the location for building a new public or private building. These parameters include walkability, energy consumption, accessibility, and visibility. For each desired location on the map, there should be a total score based on these four parameters. So that the planner can decide the best location for the construction of the structure. There is a score calculated for each parameter that is ranging between 0 and 1 and then in the end the weighted average of these parameters will be calculated to show the total score of the desired location.

1) Walkability: A walkable city is something that is important for future wealth, health, and sustainability [22]. A lot of research in the area has been done and several cities have been developing initiatives toward becoming more walkable. Walkability refers to how friendly a given region is to walking activities. In general, the analysis of walkability depends on the employed criteria, often encoded as indicators, and the objectives of the study. For example, while some city planners may be interested in analyzing walkability aspects from security or safety perspectives, others may be interested in giving more importance to the presence of amenities and attractions in a given location. To cope with such diverse analysis scenarios, the creation of frameworks and digital twin applications that support the walkability assessment according to different perspectives is of paramount importance. Such digital twins should not only support the selection of walkability indicators that make sense for the target study but also give the opportunity to users to indicate the importance of indicators (e.g., the definition of different weights).[23]

There are different definitions proposed in the research literature, common practices, and popular discussions and they can be divided into three clusters with a total of nine themes of definitions. [24]

The first cluster focuses on the means or conditions and defines a walkable area as being:

- Traversable: it refers to the basic physical condition to allow people to easily get from one place to another.
- Compactness: it refers to the existence of a short distance to destinations.
- Safety: this is concerned with crime and traffic safety.
- Physically enticing: this has to do with the possibility of the environment including full pedestrian facilities, such as sidewalks and pedestrian crossings. It may also include interesting architecture or other pleasant views.

The second set of definitions relates to the outcomes or performance of such walkable environments:

- Lively and sociable: this concerns with if the environment is pleasant, clean, and full of interesting people.
- Sustainable transportation options: this refers to the existence of suitable transportation alternatives, i.e., if it is possible to save time and energy when walking longer distances as well as give opportunities for disabled people.
- Exercise-inducing: the environment has features that lead people to exercise.

The last one uses the term as a proxy for better urban places:

- Walkability is multidimensional in terms of means and these dimensions are measurable.
- Enhancing walkability provides a holistic solution to a variety of urban problems[23].

2) Energy Consumption: World energy is growing fast and has raised many concerns regarding the environmental impact (such as global warming and climate change), exhaustion of resources, and supply difficulties. With the rapidly growing cities, the contribution of building to energy consumption has increased by up to 40% in developed countries. Growth in population, increasing demand for building services, and comfort levels, together with the rise in time spent inside buildings, assure the upward trend in energy demand will continue in the future[25].

Predicting the energy consumption of an existing building has been reviewed extensively. The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) classified the energy prediction models into two main categories, forward models and data-driven models. Machine learning models have been more popular recently due to the advancement in machine learning methods. Predicting the energy consumption of a building before construction is harder due to the limited input parameters. It can be approximated by considering the location of the building and also the elevation at which the building is going to be constructed.

In this project, since the goal is to compare the different locations of the city; the relative scores would suffice. Therefore the model ranges the energy consumption based on the location and elevation of the building compared to other locations in the city. As a result, the locations closer to sea level would have better energy scores and the higher locations will have less, due to being colder having more wind, and also needing more infrastructure.

3) Accessibility: A well-connected road network is essential for the functioning of the city and is the main part of the urban structure. A good road network provides access to the services in a city and helps the economic and social development of the city[26].

The building should be designed in a way that all people can participate in the activities they want and need to do. This is a simple definition but it is hard to be practically implemented and used since it is affected by various parameters[27].

There have been various research done in this field and some developed indexes for calculating accessibility in different situations.Shon[28] developed an index and took into account two main factors, the distance only and distance-traffic method, depending on the road network and links both of these approaches can be viable.

In this project since most of the traffic goes through the main road in the city, the distance to the main road and also the average traffic on the main road in that area were taken into account. As a result the farther we are from the main road the lower the accessibility score we get in general. The minimum and maximum possible distance from the main road and high and low traffic were used to normalize the accessibility scores for different locations.

4) Visibility: Visibility in general is a measure that ensures an object can be clearly discerned. In urban planning, visibility is important since it can affect and change the natural landscape. It is usually applied in the design phase[29]. Visibility analysis constantly explored and facilitate the process of studying city structure and urban development, especially in high-rise city models, to prevent obstructions of the urban elements, as well as to create a pleasant and well-functional environment for residents. Visibility analysis in a city landscape should take into account visual obstacles such as existing buildings and trees to be credible[30].

Visibility can be used for different means in different situations. In this project, visibility is the measure of how much of the view from the building is not blocked by other structures; therefore a building with higher visibility has a better view of the landscape and also gets more sunlight. To measure the visibility, in this project, rays will be cast outward from the building to the desired length since obstacles farther than a point will not affect the visibility of the building. Then the ratio of the rays that didn't hit any obstacles can be calculated. The values are normalized, thus lowest visibility score would be 0 and the highest would be 1.

C. Developement of the digital twin of Ålesund in Unity 3D

The app was made using the Unity 3D engine which has a lot of tools that can help make and publish the app to various platforms. Mapbox Unity API was used for the 3D visualization; this API has various functionalities that will enable us to make the terrain will elevation, 3D buildings, roads, and other layers that can be added to the map.

Using this tool, the latitude and longitude of the center of the map were defined, then layers for buildings and roads were added. These objects can have colliders, shadow casting, and can be the target of ray cast. The sun is also simulated on the map based on the coordinates of the map's center and date and time, so it will give a better and more accurate representation.

For the parameters, in the overlay part, the map is divided into square areas so that the calculations will be done for each area, to reduce the calculation time. For each area, the score of the four parameters will be calculated. A sample of walkability scores was used which has a score for each area. For the energy consumption, the elevation of each square area was calculated using the unities coordinate system and also Mapbox which can return the real-world elevation, and then the scores were normalized based on the elevations ranging from sea level to the top.

To calculate the visibility rays were cast 360 degrees from the ground level to the height of the building, using unity's physics engine the rays that hit the buildings generated from Mapbox were detected and the ratio of rays that don't build by the total number of rays was used to calculate the visibility percentage. Finally, for accessibility, we have the coordinates of the main road and traffic data for the main road. The distance from the main road was used as the main measure to generate a normalized score. This can be calculated since we have the geolocation of each area and also the coordinates of the road from Google maps data.

In the end, the final score will be calculated for each area based on the weights that the user defines and then the overlay would be color-coded based on these scores. To add a building, we have a prefab of the building model in unity, when the user hovers the mouse around the map a ray is cast from the camera to the mouse position to detect the location to place the building. When the mouse is clicked a building object is instantiated and then the parameters for this exact location will be calculated the same way as the overlay, the scores show in the UI of the app. The input data is in CSV format which is located in the project files, it can also be modified to read the data online, and the data is read and stored in arrays to be used in measurement and calculations.

III. Results and Discussion

A. The digital twin platform

In this project, a digital twin of Ålesund city has been developed, which contains a 3D map of the city with 3D building models, terrain with elevation, and roads. A real-time simulation of the sun based on the geographic location has been done in order to check the actual sun's location and shadows. There are also options to save the project and add cameras to have a view of the placed buildings from a personal perspective.

In order to find the best location for the desired building, the first tool that can be used is the overlay tool. Since we have 4 parameters for assessing the locations we should be able to prioritize them based on the specific use case. After selecting the overlay tool, we can assign a weight to each parameter (Walkability, accessibility, power consumption, and visibility) if we want to prioritize them. After this, we can click the draw overlay button and the app will divide the map

Fig. 3: Main application window

into smaller areas for each area, it calculates the score for each parameter and then the weighted average score. The overlay will be shown over the map, it is color coded and ranges from green to red, green being the best area and red the worst.

Fig. 4: Overlay

This tool gives the best areas on the map based on the desired criterion, after deciding on the best area to place the building. The next tools can be used to better pinpoint and assess the exact location. First, on the items that can be added to the map, there is an option for adding a building, by selecting this option a helper building appears at the mouse location that can be moved around by moving the mouse before adding the building on the map. If the left mouse button is clicked the building will be placed on the map the individual parameter scores will be calculated and shown for the exact location of the placed building. This will give better-detailed information for decision-making.

In the end, the user can also move around and change the time and date to simulate the sun and the shadows during the different times for the whole year. There is also an option to place a camera in different locations around the building to get the perspective of people and how the building looks from various locations.

B. Case study

In this part, we suppose we want to build a new hospital in the Ålesund area, using this tool to select the best location. At first, we prioritize the parameters to check the overview of the best areas. The weights of the parameters can be changed, and even if we don't want to take a parameter into account its weight can be set to zero. For example, if walkability is not an important factor for our building (here the hospital) and energy and visibility are the priority so the weights are as follows, energy 50%, visibility 40% and accessibility 10%. Tthe overlay can be seen in figure 5. Since we have not used walkability and accessibility as low priority, it can be seen that most areas on the map are viable.

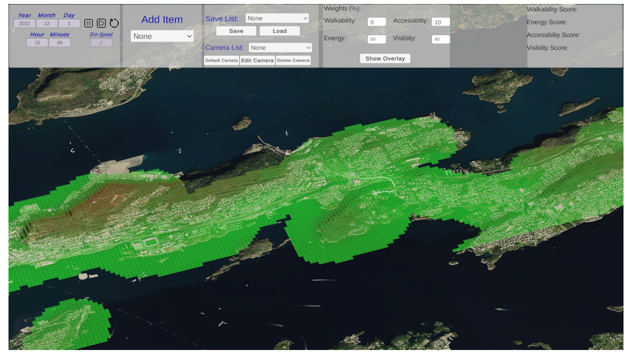

Fig. 5: The overlay based on the emphasis on energy consumption and visibility

On the other hand, if the emphasis is on accessibility (70%) and energy consumption and visibility have lower weights (20% and 10% respectively), it can be seen from figure 6, that mostly the areas that are at sea level and also closer to the main road are viable and more areas are disregarded.

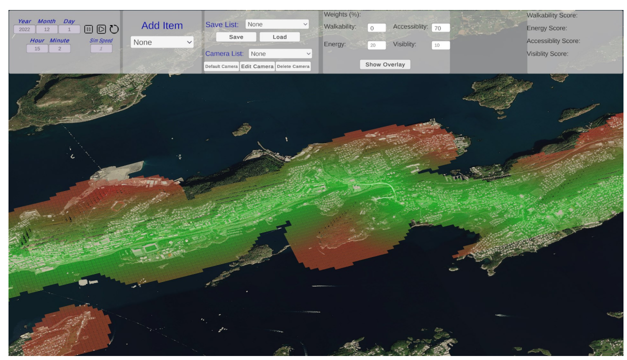

Fig. 6: The overlay based on the emphasis on accessiblity

In this case, we want all the parameters to be considered in the decision-making process. Thus the most important factor for the hospital is considered as accessibility and then power consumption, Visibility, and walkability would be next. As a result, 50% of the weight was allocated to accessibility and from the rest, 30% was allocated to energy and the rest to walkability and visibility equally. With these options selected we draw the overlay that will be used for selecting the areas. Based on the overlay three areas were selected for the placement of the building, location 1 decided to be near the city center, location 2 is near NTNU, and the last location closer to the old hospital area (Figure 7).

By placing buildings in these 3 areas we can see the individual scores for each location also how the building looks and how much space it needs. Buildings were placed at each location and the scores were collected. We can see in the

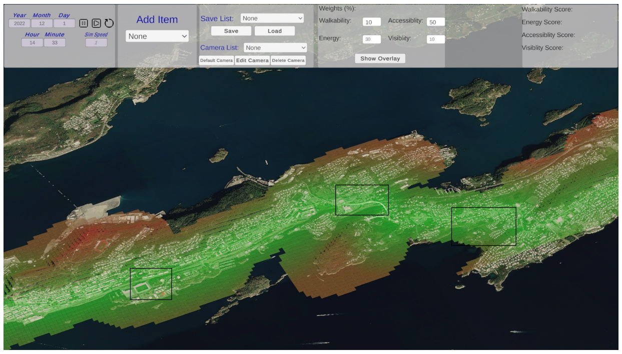

Fig. 7: Selection of general area for the hospital

table that the second location that is near NTNU is the best of these three; also we take into account that it is also near the university and is better for the collaboration between the university and the hospital.

	Walkability Score	Energy Score	Accessibility Score	Visibility Score
Location 1 (near center)	0.47	0.89	0.85	0.90
Location 2 (near NTNU)	0.36	0.96	0.9	0.94
Location 3 (near old hospital)	0.29	0.98	0.73	0.99

Fig. 8: Comparison of the 3 selected areas

Here we can see the placed building on the map, how much space it needs, and also the scores on top of the screen.

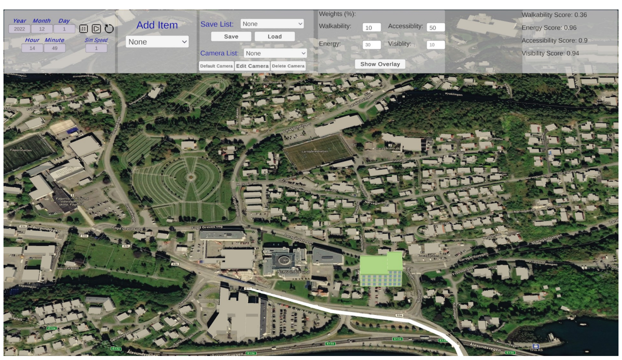

Fig. 9: The optimal selected location for the hospital

IV. Conclusion and future works

A. Conclusion

Using the data available such as geolocation, maps, roads, traffic, and walkability; the digital twin of Ålesund city was developed and used to decide on the best location for the construction of a new hospital in the city area. This tool can be used by city planners and also private people to assess various locations and help them decide on the best location for the construction of a new building; based on their desired criteria and priorities.

B. Future works

In this work, four parameters were used to assess the locations, in the future mode parameters can be added to the criteria. Also, various models can be added for each parameter to give more variety to the user. Additionally importing custom-building models by the user can also be implemented.

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