



L1.2 Semantic City Models

Lecture Notes

Author(s)/Organisation(s):

Ariana Kubart, Ocellus Information Systems AB, Sweden

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Summary

This lecture focuses fully on semantic models as the state-of-the-art-approach of the city modelling and basis for applications like smart cities and digital twins. It goes through advantages of models with semantic information and explains how such models are created. In the last part, the lecture shows several examples of existing semantic models as well as of their use in societal planning.

Learning outcomes

At the end of this lecture, the learner is expected to be able to:

Explain the semantic part of the city models and differences compared to graphical 3D models

Summarize the main steps of semantic model creation

Name examples of existing models as well as of their possible applications



Expected competences when entering the lecture

Intermediate GIS knowledge

L1.1 Concepts of 3D Modelling

Expected workload

17 slides with learning content, approximately 3 hours

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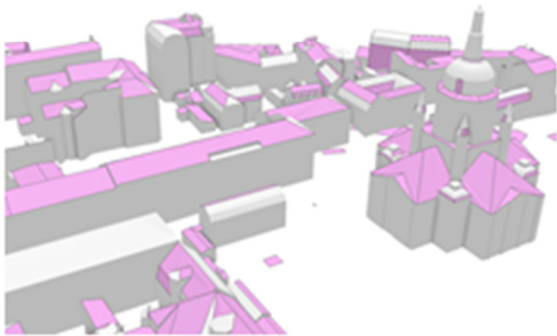


Semantic City Models



What is Semantic City Model?

Model with distinguished objects
representing real-world things: the
houses, streets, trees and others



Up: from Helsinki3D_Kalevatar Digital Twins
<https://www.hel.fi/en/decision-making/information-on-helsinki/maps-and-geospatial-data/helsinki-3d>

Left: semantic city model of Stockholm
Downloaded from: [Dataportalen \(stockholm.se\)](https://dataportalen.se/stockholm.se/)



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What is Semantic City Model?

In the last lecture, we saw that highly detailed graphical 3D city models can be automatically produced by dense matching of aerial images. Anyway, these mesh models are just “pictures”. They do not provide any information what a building is, or a street or a tree, neither what properties they have.

Surely, a human can look at the mesh model and count the trees in a given street or number of windows of a building of interest. But a computer sees only series of triangles with a texture attached to them. That is why the computer needs to define distinguished objects which represent real-world things: the houses, streets, trees and others.

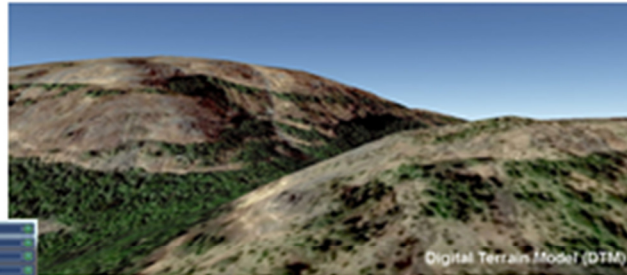
These realistic objects are labelled with their meaning. Of course they can have attributes attached to them. And even interrelationships with other objects within an area.

These structured 3D models with clearly defined realistic objects are referred as the semantic models.

Semantic City Models

Objects in the Semantic Models

- Natural objects – digital terrain model, vegetation, water bodies...



Digital Terrain Model, DTM; source: [digital-terrain-model-dtm-1024x569.jpg \(1024x569\) fspoonis.net](https://www.fspoonis.net/digital-terrain-model-dtm-1024x569.jpg)



Man-made objects and vegetation; source: Biljecki et al (2015)
Applications of 3D City Models: State of the Art Review

- Man-made objects – houses, bridges, street furniture...
- All objects can have attributes

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Objects in the semantic models

Just to remind us, the semantic models are digital representations of the objects, their properties as well as interactions among them. The objects can be both natural and human made.

The natural objects (or features) are e.g. the digital terrain model (DTM), vegetation or water bodies.

The man-made constructions are houses, bridges, streets and so on, combined with smaller objects like benches, trash-bins, traffic-lights, lamppost and other features.

Complex objects are typically further decomposed. For example, a house can be decomposed into building parts and these again into roof, walls or ground surfaces.

Walls can further contain windows and doors. As we see, this aggregation (decomposition) is hierarchical (as a building is composed of parts, which are formed of walls, which have windows).

The features can have attributes on all aggregation levels. These attributes can provide all relevant information – e.g. on the location, visual appearance, thematic attributes, functional aspects, their interrelationships, just to name any.

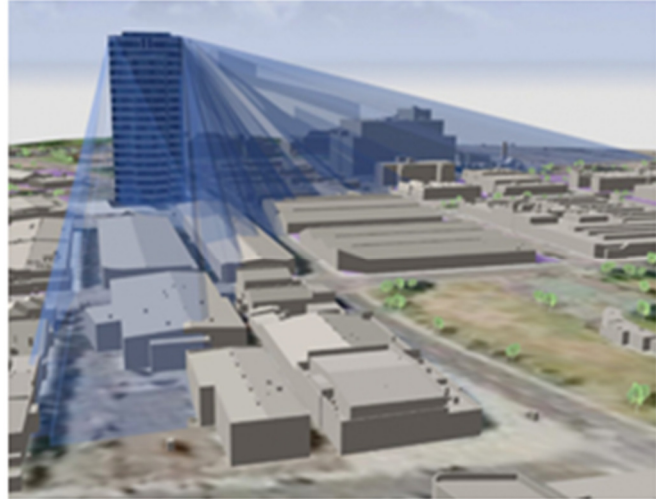


Semantic City Models



Creation of City Models I

- 3D models – successor of 2D maps
- Possible to increased computation capacity
- World is 3D – 3D models more realistic than 2D
- Certain analyses not possible in 2D, e.g. shadow-cast or air-pollution



Shadow-cast analysis, 3D necessary for it, from: Applications of 3D City Models: State of the Art Review

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Creation of City Models I

We can see the 3D city models as successor of traditional 2D maps.

Progress from 2D to 3D depended on the development and decreasing price of both scanning techniques as well as of computational capacity. As the world is in 3D, the 3D models provide more realistic information about reality, compared to 2D maps. Certain analyses are possible only in 3D space, for instance shadow-cast or air-pollution analyse.



Semantic City Models



Creation of City Models II

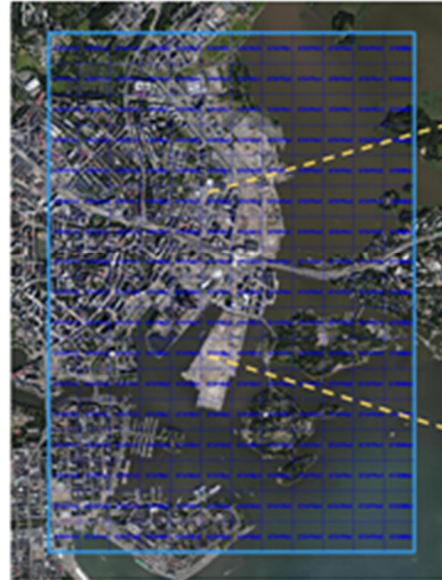
Combination of:

- aerial images (photogrammetry)
- point-clouds (LiDAR)
- 2D data (cadastres)

Data put together by specialised
software

Followed by control and manual
adjustment

Tiling of aerial images in Helsinki city model, from: The Kalasatama Digital Twins Project



Creation of City Models II

How are such 3D models created? In general, the models are based on aerial images, point-clouds and 2D data, optimally combining these techniques.

The images can be obtained by diverse photogrammetric techniques, the point-clouds origin from laser scanning (LiDAR) and the 2D spatial data from registries and cadastres, for instance.

From these data, specialised software can generate the city models automatically. It can go fast and it is cost-effective. Of course, the input data must be of good quality and properly harmonized.

Obviously, the user is able to define settings of the model calculation. And the output models can be adjusted manually later on, if it is needed for their final application.

Let's look at the creation process a bit closer and with examples.



Semantic City Models



3D City from Aerial Photos I

- 2D images from different viewpoints
- Partly overlapping
- Automatically bind together and triangulated



Vertical and oblique aerial photography (up)
and tiling into mesh 250x250 meters (right)
Source: The Kakeutama Digital Twins Project. The final
report of the KIRA-digi pilot project, 2019



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3D city from aerial photos I

2D images from different viewpoints can be enough to obtain a mesh model.

The source data consists of several partially overlapping photographs of the object to be modelled.

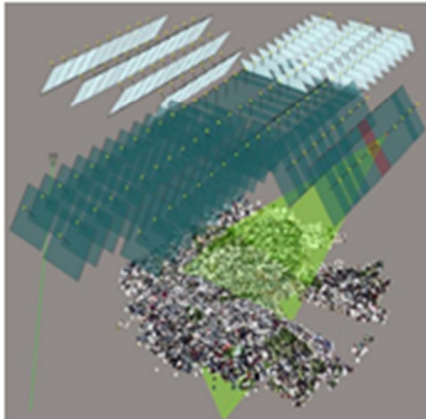


Semantic City Models



3D City from Aerial Photos II

- Binding together by finding common features in the overlapping images (down)



- Ground control points (right)

Source: The
Kalamata Digital
Twins Project. The
final report of the
KIRA-digi pilot
project, 2019



3D city from aerial photos II

These data are then automatically triangulated. The aerial images are bind together by finding common features in them.

To anchor the 3D model to the reality, one needs to define ground control points and specify their X, Y and Z coordinates. These ground points represent easy-to -distinguish places, such as road crossings. Their location must be determined manually so that they both cover and encloses the entire area.

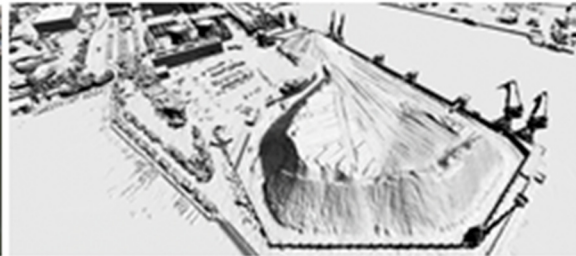
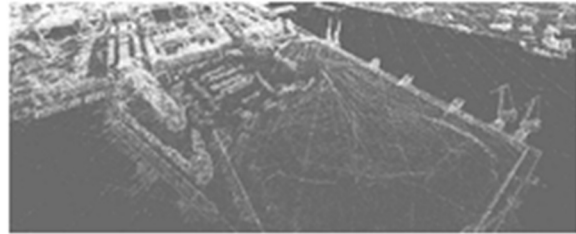
The resulting model looks highly realistic, and its quality can be checked by visual inspection or by comparing the model to the laser scanning data. We can see an example of the Helsinki model on the next slide.

Semantic City Models

Example of Helsinki model

Three steps in creation:

- 1) point-cloud from aerial-images (right up)
- 2) mesh model without visible triangles (right down)
- 3) final photorealistic model (left down)



Source: The Kalasatama DT Project

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Example of Helsinki 3D model

The slide demonstrates the three steps in creation of Helsinki mesh model based on aerial images.

The upper left image illustrates the first step, i.e. a point-cloud obtained from the aerial-images.

Next image below the first one shows the mesh model, in this case without the visible triangles.

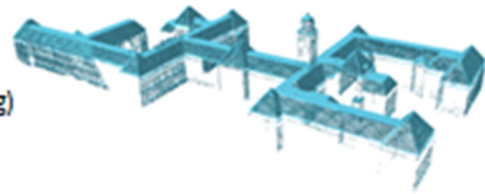
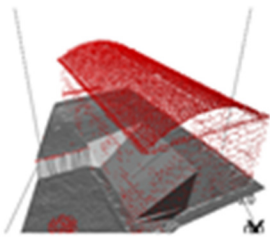
The final photorealistic model, with projected aerial photographs, is shown by the last image down on the right side of the slide.

We can see that the model is highly realistic. However, the individual objects are not defined yet.

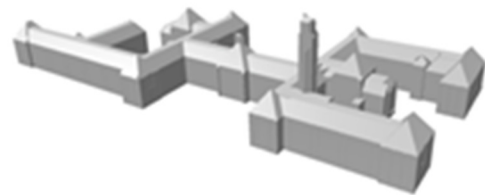
Semantic City Models

3D city from laser scanning I

- Mesh-models even from point-clouds (right (a) a point-cloud, (b) reconstructed building)
- Can be photorealistic (down)
- Smaller areas, more details (vs. aerial images)



(a)



(b)

Source: 3D Book (left),
<https://www.rock.es/ia/blog/a-tour-of-3d-points-cloud-processing> (right)

3D city from laser scanning I

Mesh models can originate even from point clouds from laser scanning. In general, this method is suitable for smaller areas and can result in more detailed models, compared to the image-based method.

It is even possible to project photos onto the model to get it photorealistic.



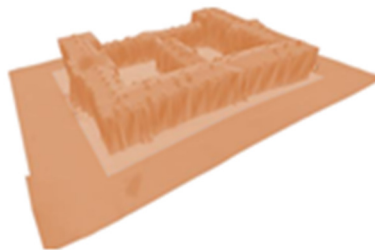
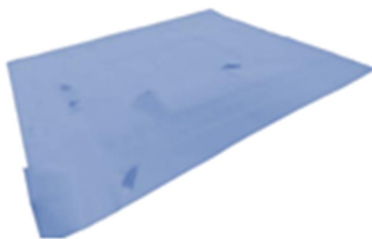
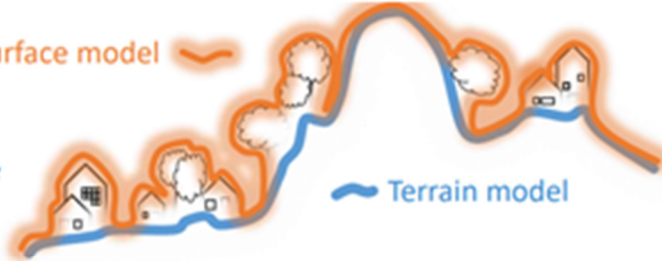
Semantic City Models



3D city from laser scanning II

Surface model

DTM – elevation of building footprint
DSM – building height and roof shape
2D map – footprint



- DTM and DSM – Digital Terrain and Surface model (up)
- Terrain and surface models from one building area (left)

Source: The Katsutama DT Project

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3D city from laser scanning II

Great examples of LiDAR-based point-clouds are Digital Terrain Model, DTM, and digital surface model, DSM. These are often freely available for users and can be used to generate city models from them.

The terrain model determines the elevation of the building's footprint; the surface model identifies the height and roof shape, and the footprint is available in any 2D map.

With the height, roofs and footprints available, it is possible to identify individual city objects as well as to assemble the walls. And even this can be processed more or less automatically.

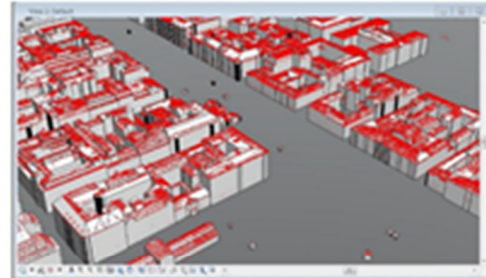
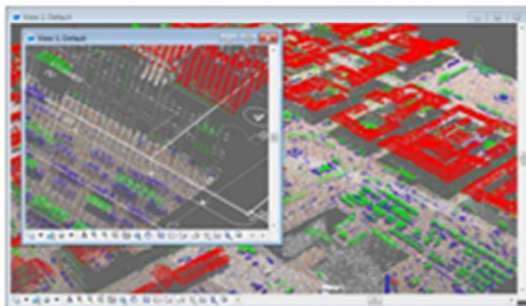


Semantic City Models



3D city from laser scanning III

Base map and point-clouds for an area (down)
Roof shapes of buildings from the data (right up)
Geometries of created 3D buildings (right down)





3D city from laser scanning III

The figures on this slide demonstrate the process of object creation and identification, as describe in the previous slide.

The area example is again from the Helsinki 3D model.



Semantic City Models



Co-funded by the European Union

Final 3D semantic model

- Adding semantic info = attributes
- Available e.g. in cadastres



Examples of graphical semantic model of Stockholm – city center and a residential area

<https://semantic3d.stockholm/2020/03/09/over-100-000-byggnader-i-stockholm-3d-modellen-i-sats-pa-byggnadskomplex-mpa-databas/>

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Final 3D semantic model

Following the steps from the previous slides, a city-model with individual objects gets ready. Obviously, it is possible to project air-photos onto the model in order to get realistic façade appearances.

How such a model looks like in the end can be seen on the slide, this time as examples from Stockholm.

But to get a real semantic model, we also need to add the attributes, that is to say the semantic information. It can be everything from object owner and usage to number of persons living at the given address. This information is available in cadastres, for instance, so it is just to connect it with the model.



Semantic City Models



Abstraction in 3D models

- Removing unnecessary parts, e.g. interiors
- Semantic models– high abstraction level, unique IDs
- Mesh models– low abstraction, less computer space, faster to create and read, cheaper



[Helsinki 3D | City of Helsinki](https://www.hel.fi/en/decision-making/information-on-helsinki/maps-and-geospatial-data/helsinki-3d)

<https://www.hel.fi/en/decision-making/information-on-helsinki/maps-and-geospatial-data/helsinki-3d>

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Abstraction in 3D city models

We have seen that 3D modelling is done through a series of abstractions of the real world. Some information gets lost, but, hopefully, the remaining information is more structured and meaningful in the end.

The abstraction can remove unnecessary parts, such as interiors in a city model, and can work at different levels.

Semantic 3D models are typical examples of high abstraction level with the world divided into discrete objects. All these objects should have globally unique identifiers, stable over the whole object-lifetime. This allows both to keep track as well as to update the objects in different applications.

Mesh models based on triangulation represent a lower abstraction level, but are faster and cheaper to create. As discussed, it can be the first step of the 3D-modelling, which can be followed by semantic decomposition later on.

In general, the first generation of the city models was based on the meshes. Nowadays, some cities upgrade their models into semantic ones that could serve as a basis for a digital twin. Of course, the more a city's model is enriched with information, the more functional and useful its digital twin becomes.

There is a specialised course on Digital Twin in this Course module (3D GIS).

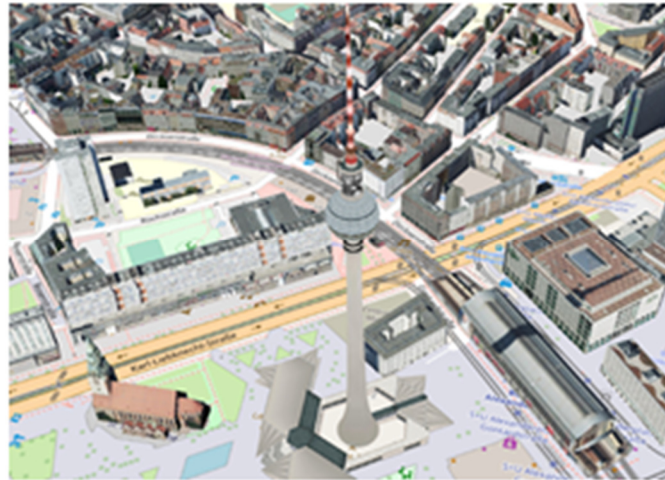


Semantic City Models



Examples of 3D city models

- Semantic models- mainly public sector
- High-graphic models– often commercial, Open Street Map
- 1st free model – Berlin 2015



[VisualizationBerlin – 3DCityDB Database](#)

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Examples of 3D city models I

To remind us, the 3D city-models can be seen as successors of traditional 2D digital maps. This advance was possible thanks to increase of both computing and storage power, as the 3D model contains significantly higher amounts of data, compared to the 2D maps.

Majority of semantic city models are created and maintained by mapping departments on municipal level.

Anyway, 3D city models are also produced by commercial companies as well as by initiatives like the Open Street Map project. These are often graphical, not semantic, though.

The first freely available city model was that of Berlin, published in 2015. It was automatically generated from 2D cadastre and airborne laser data, with textures automatically extracted from aerial images, as we explained above.



Semantic City Models

Examples of 3D city models II

Many cities provide
3D models to browse

Data itself usually not
for free to download

Exceptions:

[Cities/regions around
the world with open
datasets \(tudelft.nl\)](#)



Semantic model of Zagreb, Croatia

[203D: 3D model Grada Zagreba \(gdi.net\)](#)

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Examples of 3D city models II

The Berlin model, mentioned above, is open. Similarly, there are other models of diverse cities from many countries. For a list of them, see a list provided by Delft Technical University:

[Cities/regions around the world with open datasets \(tudelft.nl\)](#)

These open models are in diverse formats, but only a minority of them is semantic, though.

The majority of cities are creating their 3D models nowadays. However, they do not provide them for free, or at least not in higher LoD (e.g. LoD1 can be open data, but LoD2 has one to pay for).

Swedish examples of advanced semantic models is those of Stockholm and Göteborg.

[Stockholm 3D](#)

[Digital tvilling - Göteborgs Stad \(goteborg.se\)](#)

The figure on the slide illustrates semantic LoD2 model of Zagreb, Croatia.

[ZG3D: 3D model Grada Zagreba \(gdi.net\)](#)



Semantic City Models



Applications using semantic 3D models

- Visualisation & city planning (see figure)
- Queries – depends on LoD and depth of semantic information
- Analyses and simulations – provide new semantic information
- Scenario testing



Source: The Kalasatama DT Project

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Applications using semantic 3D models

There are many possibilities how to use the 3D city models.

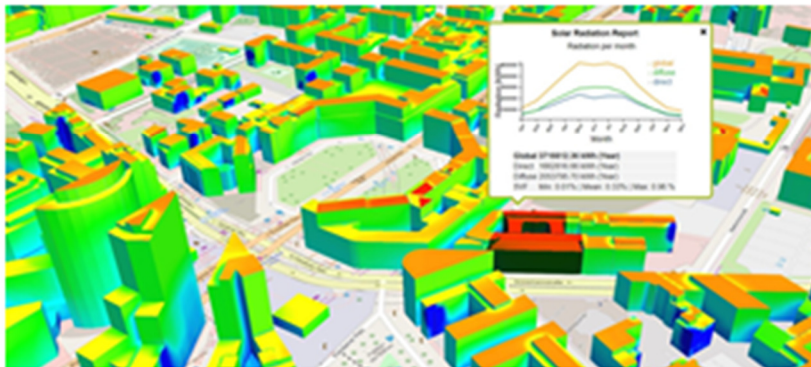
The first is the visualisation, both of the existing buildings and of the planned ones. This is illustrated by figure on the slide, showing a newly planned neighbourhood in Helsinki. This is of course highly useful in city-development.

But one can get much more information out from the semantic models, as all city objects can be enriched with thematic data. It is possible to query, for instance: “How many lamp-posts are in a street” or “How many windows of a house are oriented to a square” or “How many buildings consume more energy than 100 kWh/m²/year “. The queries can be as complex as the semantic information and LOD allow.

One can also perform diverse analyses and simulations, as well as test different development-scenarios in that way. Results of such analyses can even provide new semantic information. Many of the analyses are already used in practice, even if definitely not in all the cities.

Semantic City Models

Analysis of solar radiation



[3d-visualisation solarpotentialanalysis-expectatio-20-9-3.jpg \(2330x1040\) \(v-systems\)](#)

Possibility of many
calculations:

- Solar energy production
- Best roofs for solar-cells
- % of house-consumption covered by solar-energy
- Money spent on electricity

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Analysis of solar radiation

We are going to look at some concrete application examples.

Figure on the slide shows estimated solar radiation on roofs and facades in a German town. From that number, it is possible to count how much solar energy can be produced in the area, or which roofs are the most suitable to mount solar-cells on.

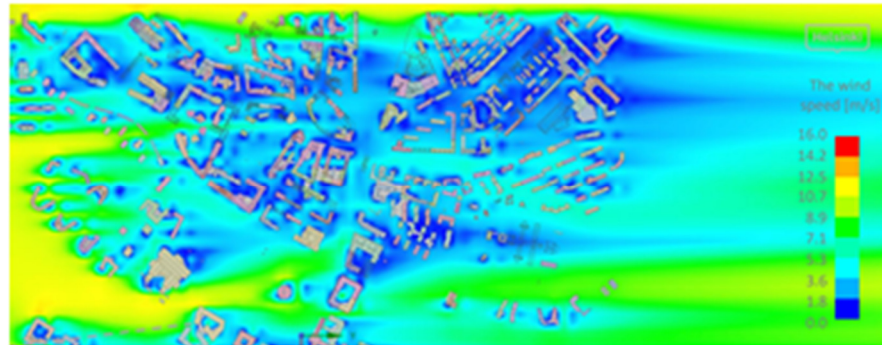
Would we know how much electricity houses consume, could we count percentage of the consumption covered by the solar-cells or even how much money a household can spare yearly on electricity-bills. Or if the house can become Net-zero-energy building, without and with improvement of its thermal insulation parameters.

As we see, the analyses might be highly complex, if the model provides relevant semantic information.

Semantic City Models

Analysis of wind speed

- Slowing of the wind-speed in newly planned neighbourhood
- Estimating thermal-comfort during hot summers
- Spreading of air pollution



Stimulation of wind intensity on street level in Helsinki
The wind blows from the left side of the picture in 15m/s
Source: The Kalasatama DT Project

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Analysis of wind speed

With the next application examples come we back to Helsinki, to the newly planned neighbourhood of Kalasatama.

The figure shows how a strong wind from the sea would be slowed down by the planned buildings and how pedestrian wind-comfort would be.

Similarly to the solar radiation, wind-speed and direction can provide data to numerous other analyses. For instance, one can count thermal comfort and wind cooling effect in cities during the hottest days, which is important in the cities with increasing maximal temperatures and lethal heat-waves.

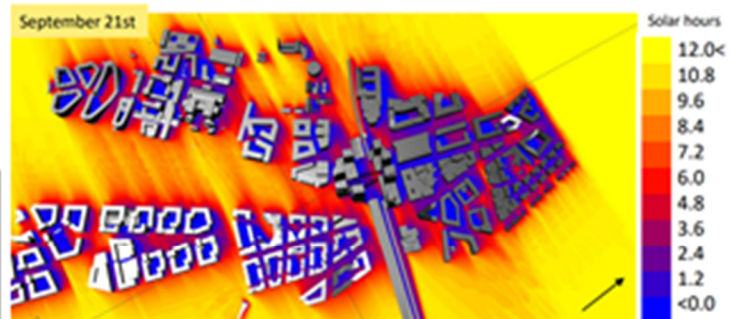
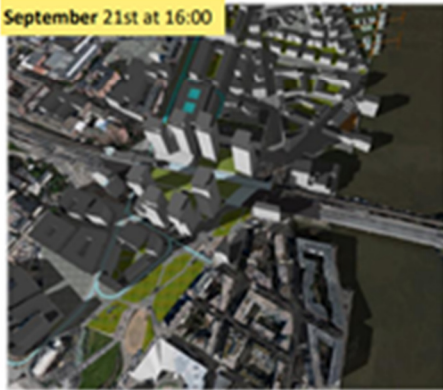
Wind speed and direction is also crucial when simulating air- and noise pollution, as required by European Noise- and Air Quality directives. (More about it in the third block of this course).

Semantic City Models

Sunshine and shadow analysis

- City planning

September 21st at 16:00



- Sunshine (up) and shadowing by planned-buildings (left) at autumnal equinox
- Similar computations for any time of the year
- Testing building-design and position

Source: The Kalasatama OT Project

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Sunshine and shadow analysis

The next example is again from the Helsinki Kalasatama neighbourhood.

The figures visualise results of sunshine analysis and how the shadows of the newly-planned houses will lay at autumnal equinox.

Of course that such analysis can be counted for any time of the year. It reveals which yards and streets with very little or no sunshine in different seasons.

It is possible to test different scenarios of the building disposition and design, in order to choose the most suitable variant.

Semantic City Models

Other applications

- Heavy-rain events and flooding
- Digital Twins, Smart Cities
- Data quality and harmonisation fundamental
- Biljecki et al. (2015): Applications of 3D City Models: State of the Art Review



[Applications of 3D city models | CityJSON](#)

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Other applications

Other important application in city-planning is flooding analysis, where one can test different scenarios of heavy rains and see if the locality will become inundated or not. This is increasingly important as the extreme-weather events will be more and more common.

Then, there are the concepts of Digital Twins and of Smart Cities. The idea is that diverse sensors would collect information in real-time and provide immediate feedback on city functions. It can include everything from regulation of traffic jams and air-pollution to smart trash-bins, asking themselves to be emptied when they get full.

Other applications are still in the beginning, like to use the models for navigation and training of autonomous cars or use VR-goggles to provide a virtual walk through newly planned developments.

Of course, there are many other applications. An overview paper from 2015 describes more than 100 of them.

[Applications of 3D city models | CityJSON](#)

Whatever application one would run, it is important to know that preparatory work is fundamental. If information in the model is structured in a consistent way and includes aspect that is really needed for the application, the simulation itself can run more-or-less automatically.



References

The Kalasatama Digital Twins Project. The final report of the KIRA-digi pilot project, 2019

Biljecki et al. (2015): Applications of 3D City Models: State of the Art Review, ISPRS Int. J. Geo-Inf. 2015, 4, 2842-2889; doi:10.3390/ijgi4042842

Ken Arroyo Ohori, Hugo Ledoux, and Ravi Peters (2020–2022): 3D modelling of the built environment, available at: [Releases · tudelft3d/3dbook \(github.com\)](https://tudelft3d.github.io/3dbook/)