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Applications of 3D City Models for a better understanding of the Built Environment

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Abstract The administration of modern cities is a complex task involving various disciplines. To satisfy their specific needs regarding planning and decision making, all of them require a virtual representation of the city. Semantic 3D city models offer a reliable and increasingly available virtual representation of real world objects in an urban context. They serve as an integration platform for information and applications around the city system, because data from different domains can be linked to the same objects representing real world urban objects. This work gives an overview on the current state of applications based on semantic 3D city models and how they can be categorized. Three use cases are explained in detail. Based on city models according to the CityGML standard, first a tool for estimating the solar irradiation on roofs and facades is introduced. By the combination of a transition model, sun position calculation, and an approximation of the hemisphere the direct, diffuse and global irradiation as well as the SkyViewFactor are computed. Second, an application for the simulation of detonations in urban space is presented. The city model is converted to a field-based representation for running a Computational Fluid Dynamics (CFD) simulation. By storing logical links between the object and the field-based representation of the city model, information exchange between the simulation tool and the city models is realized. The third application demonstrates the estimation of the energy demand of buildings based on official statistical data and the simulation of refurbishment measures. All three applications use a cloud-based 3D web client for visualization of the city model and the application results including interactive analysis capabilities.

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1 Introduction

Virtual 3D city models have been used for many years to capture and explore the view of a city. Visualization and visibility analysis have been (and still are) key applications. The requirements on a 3D city model for these type of applications are rather low. Basically, a Digital Surface Model (DSM) is used to describe the geometry of the Earth's surface – including the shape of the natural and built environment like trees or buildings. In addition, photographic images are mapped onto the DSM providing color and appearance information. Due to major progress in photogrammetry and remote sensing technology and methodology over the last ten years these 3D models can be generated from airborne or terrestrial mapping campaigns in a fully automated way. Good examples are the 3D models provided in Google Earth or in Apple's map application.

While the visual aspects of the built environment are well covered, the beforementioned models do not carry any knowledge of what they are representing. Visualization models in principle just consist of geometric elements like 3D polygons, volumes, or meshes with additional appearance information. The interpretation of the rendered 3D model happens completely by the (human) viewer relying on his capability to recognize and discriminate the individual urban objects like buildings, bridges, roads, trees etc.

The administration and development of modern cities is a complex task involving many disciplines, each of them with their own requirements. To satisfy their specific needs regarding planning and decision making, all of them require a virtual representation of the cityscape, that allows for much more than mere visualization. For instance, to determine the total roof surface area of a city quarter, information on which surfaces represent roofs and a geometric representation allowing area calculation are indispensible.

Semantic 3D city models not only represent the shape and graphical appearance of urban objects but contain semantic information describing their thematic proper-

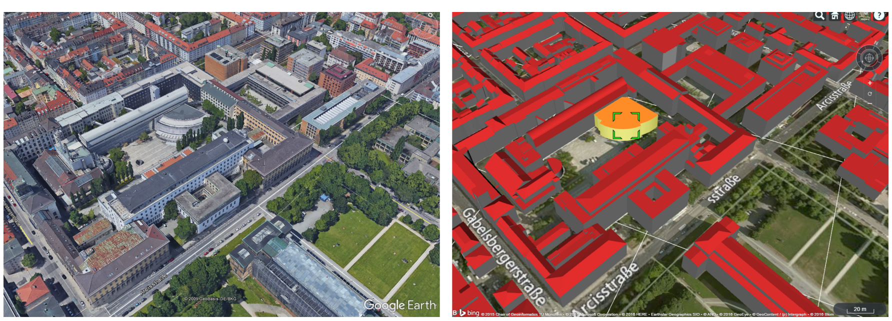

Fig. 1 Comparison of visualization only (left image, source: GoogleEarth) and semantic 3D city models (right image, source: State mapping agency of Bavaria (LDBV)): While the visual quality is higher in the visualization model, individual objects, as for instance the highlighted building, can be discriminated computationally within the semantic model.

ties, taxonomies, aggregations and interrelations. As depicted in Fig. 1, the visual quality of semantic 3D city models (right image) may be lower than in visualizations models (left image), but it is possible for machines/algorithms to distinguish urban object like builidings (see highlighted building in the right image) and use their rich thematic and geometric information for queries, statistical computation, simulation, and visualization. Driven by the growing availability of semantic 3D city models and the expanding number of thematic classes for different object types (e.g. roads, vegetation, bridges, tunnels, etc.) new applications in the context of urban planing arise. In the following, we introduce the main modelling concepts and show selected application scenarios that demonstrate the added value of semantic 3D city models coping with current social, ecological, and economical challenges.

2 Semantic 3D city models and CityGML

The international standard City Geography Markup Language (CityGML) is an open data model and encoding format that has been developed for the representation and exchange of *semantic virtual 3D city and landscape models*. CityGML comprises information on the geometry, appearance, semantics and topology of objects in an urban context. The city objects are decomposed following logical criteria which can be observed in the real world according to the ISO 19109 definition of geographic objects [24]. The exchange format defined by CityGML is based on the Extensible Markup Language (XML) and the ISO 19100 standards family, for instance the ISO 19107 standard [21]. The standard is an application schema of the Geography Markup Language version 3.1.1 (GML3). Its latest issue, version 2.0.0, was released in 2012 as an official standard of the Open Geospatial Consortium (OGC) [33].

The CityGML standard was designed to serve as a universal topographic information model independent of specific subject areas. It defines a common understanding of the segmentation of the most relevant features classes of a city and their attributes. Hence, the standard serves as an information model for a broad range of applications like urban planning, civil engineering, environmental simulations or tourism. Fig. 2 gives an overview on the modular structure of CityGML. Based on a core module 10 thematic modules for e.g. buildings, transportation systems or vegetation are defined which can be freely combined according to the given application context [33].

However, in practical applications it is frequently required to store and exchange additional information, which is not covered by the predefined classes mentioned above. Therefore, CityGML supports two extension mechanisms, *generics* and *Application Domain Extension (ADE)* as shown in Fig. 2. All city objects can carry an arbitrary number of *generic attributes*, which are defined by a name, data type and value. Moreover, *generic city objects* with arbitrary geometries and generic attributes can be defined. The second extension concept are so called ADEs. ADEs allow the extension of existing thematic modules and the creation of new feature

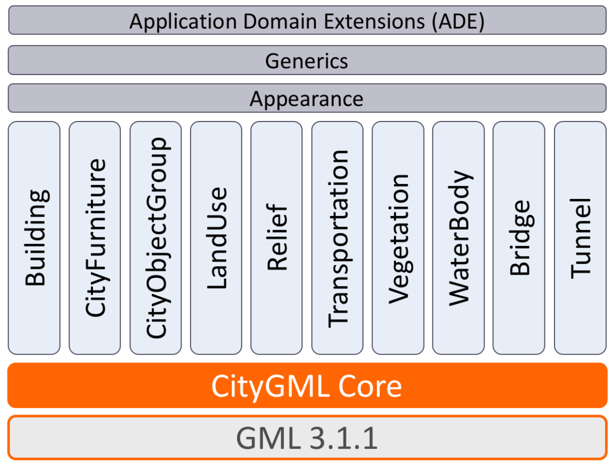

Fig. 2 Modularization of CityGML. Vertical modules contain the semantic modeling for different thematic domains. The horizontal modules contain core functionality and mechanisms for different kinds of graphical appearance of city objects and for extending the predefined thematic modules.

classes. In contrast to generics, ADEs are defined in a separate XML schema definition file with their own namespace. Hence, they are formally specified and instance files can be validated against the schema of the ADE [33]. An example ADE for modelling traffic noise emissions (Noise ADE [10]) is provided within the CityGML 2.0 specification [17]. Other popular ADE examples are the Energy ADE extending the CityGML model with features for building heat demand [44] and the currently developed Utility Networks ADE enabling the modelling of supply and disposal networks for analysing the urban supply situation [2, 3, 36].

On the subject of variable resolution requirements of different applications, CityGML supports a multi-scale representation of objects with five consecutive Level of Details (LoDs). Objects become more detailed both geometrically and thematically with increasing LoD. Each object can be stored in different LoDs simultaneously, allowing its analysis and visualization according to the degree of detail, the given application context requires. Level of Detail 0 (LoD0) is a coarse representation of the earth's surface, Level of Detail 1 (LoD1) is the well know blocks model, where all 3D objects are created by vertical extrusions of footprints. Level of Detail 2 (LoD2) offers distinctive roof structures for buildings, while Level of Detail 3 (LoD3) denotes architectural models with detailed wall and roof surfaces, windows and doors. Level of Detail 4 (LoD4) adds building interiors like rooms, stairs and furniture. The LoD concept applies to all other CityGML features types as well [33].

Semantic 3D city models are predominantly created and provided by public mapping agencies, which ensures their sustainable maintenance and updating. They are derived in fully or semiautomated workflows from official 2D cadastral data and elevation information from airborne laser scanning or aerial images. However, the automated creation of CityGML models based on open data is feasible as well. Kolbe et al. [34] created a model of New York City based on 26 different data sets from the New York City Open Data Portal, comprising all buildings, land parcels, roads, parks, the digital terrain model, and water bodies – all with 3D geometries and between 10 and 80 thematic attributes. At the national level the Working Committee of the Surveying Authorities of the States in Germany (AdV) is prescribing a uniform and nationwide dissemination of building models in Germany by the mapping agencies. In Germany, almost all of the existing buildings are currently available in LoD1. This comprises more than 50 million single building objects. As of December 31th, 2016 models in LoD2 for the total building stock are available for the German states North Rhine-Westphalia, Rhineland-Palatinate, Saarland, Saxony, and Saxony-Anhalt with most other german states to be completed by 2018 [1]. At the European level, a unified and standards-based availability of building models is determined by the Infrastructure for Spatial Information in the European Community (INSPIRE) directive [23]. As one of 34 themes, the theme *Buildings* is covering building specific data for different use cases. Gröger et. al. [18] are proposing a CityGML-based encoding for the INSPIRE Data Specification on buildings allowing their use as CityGML buildings and thus bridging the gap between political requirements and data availability for semantic 3D city models.

The upper part of Fig. 3 shows some examples of the large number of international cities such as Singapore, Paris, Zurich, Vienna, London, New York, Vancouver, Montreal, and Helsinki that provide and maintain a semantic 3D city model. The federal German state North Rhine-Westphalia and the city of Berlin are even distributing their city models at no charge for both commercial and non-commercial

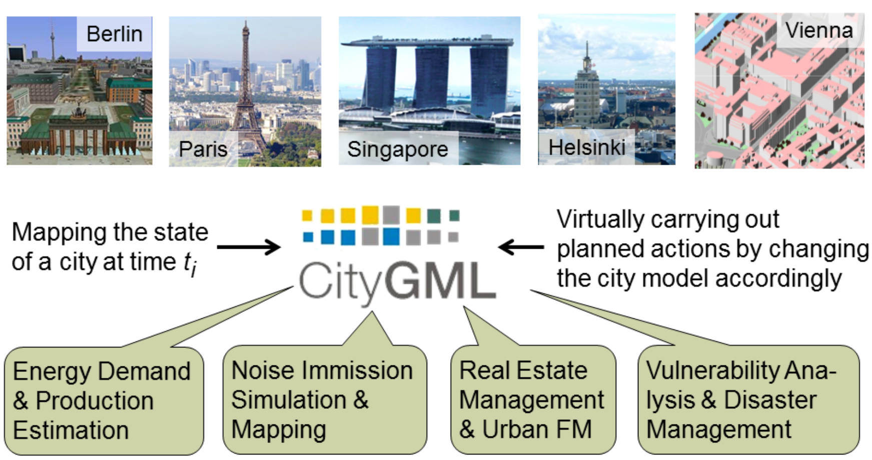

Fig. 3 Semantic 3D city models serve as information hub for different application scenarios from various disciplines. The CityGML standard harmonizes access to the most common urban features. Thus, applications that are based on the standard are guaranteed to work among different cities.

use to foster the usage of the data and accelerate the development of new applications. These applications cover, amongst others, energy demand and production estimation, noise immission simulation and mapping, real estate and urban facility management and vulnerability analysis and disaster management. To ensure, that these tools can be applied in cities all over the globe, a common understanding of the most important urban features and standardization of the underlying data model and exchange format is required. This enables software developers to design tools for a broader audience and facilitates data exchange between software components of different domains and development teams based on the objects of the city model.

3 Applications of 3D city models: An overview

Today, 3D city models are used in a wide range of applications covering diverse use cases and application domains. The work of Biljecki et al. [4] gives an extensive overview on the current utilization of 3D city models and introduces a hierarchical terminology for their segmentation, which is briefly recapped in the following.

According to Biljecki et al., the biggest issue, avoiding a straight forward inventory of applications of 3D city models, are many undefined terms in the context of 3D spatial information like use case, application, or operation. Even the definition of 3D city models is not consistently used. Hence, a well-defined categorization of 3D city model applications based on *application domains*, *use cases* and *spatial operations* is not feasible as these terms are overlapping.

Therefore, the authors decided to focus on the listing of use cases. Additionally, applications for a better understanding of the individual use case are collected. When trying to find a taxonomy for use cases, that is both mutually exclusive (a use case can only be part of one category) and collectively exhaustive (all categories cover all use cases) the only valid criteria that could be identified is the visualization aspect. Hence, use cases are categorized into the two following groups.

One the one hand, *non-visualization* use cases are described, which require visualization neither of the 3D city model nor the results of the spatial operations the use case comprises. For instance, the solar potential analysis discussed in Sect. 4, an application of the use case of estimating solar irradiation, falls into that category. The simulation results can be visualized, but this is not essential to achieve the purpose of the use case. The information the simulation generates is meant to be used for the identification of suitable areas for solar energy generation. As the results are written to a database, this task can be performed using a query without visualization.

On the other hand, the authors delineate *visualization-based* use cases. They include cases, where visualization is very important but not essentially required. An example for this is navigation, which works fine with state-of-the-art text to speech software, but greatly benefits from visualization. Second, visualization-only use cases, like virtual reality or communication of urban information are covered by that category. This categorization is consistent with the separation into visual 3D models and semantic 3D city models as described in Sec. 1.

In an extensive literature review, the authors identified more than 29 use cases including more than 100 applications, which are arranged into theses categories. The non-visualization use cases comprise the estimation of solar irradiation, energy demand estimation, aiding positioning, determination of floorspace and classification of building types and is much smaller than the visualization-based use cases category, that includes more than 20 entries. A complete list of the use cases and a brief description of the included applications can be found in the original work of Biljecki et al. [4]. A brief summary of the most important use cases grouped in four topics is given in the following.

The topic *energy* comprises the use cases of estimating solar irradiation and building energy demands. To compute the insolation on a building the geometric information of the city model building surfaces like the inclination, orientation and area is taken as input for solar empirical models to evaluate its suitability for solar energy generation (photovoltaics (PV) or solar thermal collector (ST)). Please find a detailed application example in Sec. 4. For the estimation of the energy demand of a building both geometric and thematic properties of the city model are taken into account. The combination of a buildings' volume, shared wall surface areas and its construction year allows the estimation of its heating energy demand, as discussed in the detailed example given in Sec. 6.

The second topic is *homeland security and vulnerability*. One of its central use cases is visibility analysis, where the Line of Sight (LoS) between two points is computed based on the geometries of the city model. For instance, this information is used for optimizing the placement of security cameras [63] or evaluating the hazards of sniper terrorism [59]. Another relevant use case in this context is emergency response. 3D city models contribute valuable information for the preparation for emergency situations and quick response scenarios like building entry points (doors and windows) or even detailed indoor models for improving evacuation planing or fire fighter ladder positioning [9, 37, 54]. Becker et al. [2] use 3D city models including utility networks [36] for estimating cascading effects of critical infrastructure failure in cases of disasters or emergency situations. Moreover, an application example applying a Computational Fluid Dynamics (CFD) simulation for the assessment of blast effects in an urban context based on the thematic and geometric information of 3D city model buildings is discussed in Sec. 5.

The most relevant use cases for the third category, *traffic and mobility*, are visualization for navigation and routing. 3D city model objects like buildings are often familiar landmarks that help users with orientation in navigation applications. The 3D geometry representation of city models is more realistic than the symbolic representation provided by 2D maps and contains more navigation cues [46, 48]. Moreover, semantic 3D city models allow for optimizing the 3D view based on the thematic information they provide [39, 43]. 3D city models have gained interest for routing purpose as 3D navigation techniques become available [22] and they contain objects that, are not available in 2D maps like steps and ramps, that, for instance, influence the navigable space for pedestrians [52]. If the 3D city model contains information on the interiour of buildings, this information can be use for way finding and accessibility applications [29, 30, 31, 38, 55].

Climate and environment is the fourth topic. Its most prominent use cases are the estimation of noise propagation and CFD simulations for various phenomena including flooding. The estimation of noise propagation benefits from 3D geometries, as the noise level varies for different height levels due to refraction [35]. Semantic informations can be used to obtain noise propagation simulation parameters like traffic density, as the work of Czerwinski et al. [10, 11] shows. 3D city models are a common basis for CFD simulation. Most applications are found in field of microclimate analysis for e.g. evaluation of air quality and pollutant dispersion [57], wind comfort [25] or the urban thermal environment [40]. Estimating the extend and impact of flood events can be enhanced compared to 2D methods using 3D city models as well [49]. The multi-resolution flood simulation approach developed by Varduhn at al. [60] utilizes the drainage system of a City Geography Markup Language (CityGML) city model to include pipe network interactions an allow predictions for individual buildings. As discussed in Sec.5, the exchange of semantic information between simulation system and city model can be beneficial for both sides.

4 Estimation of solar irradiation using semantic 3D city models

Solar irradiation is a clean, silent, secure and abundantly available energy source. Due to decreasing costs and improvements in technology and acceptance, Photovoltaics (PV) and solar thermal collectors (STs) are going to play a key role in the future energy production, especially in urban areas where a significant portion of the energy is consumed. In 2010, the EU Directive 2010/31/EU introduced the Nearly Zero Energy Buildings concept, requiring that the local energy production of all new buildings after the year 2020 covers their local energy demand. PV and ST systems foster this concept of decentralized energy production due to their high modularity. Furthermore, transmission and distribution losses are avoided, as the energy is produced at its point of use [5, 47].

To meet the requirements of EU legislation, in the future much larger areas for PV will be required. As facades are much larger than roofs in modern cities and are mostly devoid of building installations and infrastructure like chimneys, dormers, air conditioning units or elevator engines and usually present better maintenance conditions than PV panels on roofs, as vertical surfaces do not accumulate so much dust and are usually free of snow in the winter, they increasingly gain interest for deployment of PV in residential areas [47]. Moreover, the combination of energy production with other building functions like heat insulation, cladding or illumination with semi–transparent photovoltaic modules may offer interesting benefits [6].

For the successful deployment of PV and ST systems in the urban area, the local potential of roofs and facades needs to be investigated, taking influencing variables like the local meteorological and climate conditions and shadowing effects of the surrounding topographic features into account. Semantic 3D city models are an ideal data source for such assessment as they combine a detailed representation of the cityscape with visualization and analytic capabilities.

4.1 Estimation of urban solar energy potential for facades and roofs

The method for estimating solar irradiation in urban areas introduced in this section is based on the Master's Thesis of Wolfgang Zahn [66]. His work has been revised and implemented in Java, as a plugin for the 3DCityDB Importer/Exporter, the standard database management utiliy for the 3DCityDB for CityGML (3DCityDB). The application has been enhanced for increased performance and functionality with the main objective to develop a user-friendly tool that enables non-expert users to perform and evaluate solar potential analysis for city models of arbitrary size.

The model computes the direct and diffuse solar irradiation and the SkyViewFactor (SVF) for roofs and facades considering shadowing effects of buildings and a Digital Terrain Model (DTM) while ignoring the influence of reflected radiation. Ground features are not being processed, as those areas are usually not available for solar energy generation in cities and would needlessly increase runtime. The only input data required is a 3D city model in Level of Detail 2 (LoD2) according to the City Geography Markup Language (CityGML) standard, where building roofs and facades are modeled as thematic surfaces [17]. Optionally, a DTM can be integarted as well.

The direct solar irradiation is modeled using a combination of the transition model developed by Fu und Rich [15] and an algorithm for computing the position of the sun from the work of Grena [16]. First, the sun positions for one year are computed for a freely selectable observation point with geographic coordinates given in Latitude (LAT) / Longitude (LON) and height above sea level. Usually, the center of the city model is beeing used. Time intervals between the sun positions can be configured in steps of hours and days where typically an one-hour-interval is selected, considering performance and quality aspects. The sun positions are described by two angles, one for orientation (azimuth α) and the other for height (zenith θ) relative to the observation point applying an algorithm introduced by Grena [16] providing a maximum error of 0.19°. The resulting sun positions are stored as point features in a radius of 100 000 km around the observation point in the Coordinate Reference System (CRS) of the city model in the 3DCityDB with their radiation power as attribute. Second, the radiation power [$\mathrm{kW\,h\,m^{-2}}$] of each sun point is calculated using a simplified transition model based on Fu and Rich [15] considering the transmissivity (τ) of the atmosphere depending on the height of the sun point and the relative optical path length $m(\theta)$.

For robustness against regional atmospheric differences the transmissivity and the fraction of the diffuse irradiation of the global irradiation are calibrated using freely available data from the NASA Atmospheric Science Data Center. Implementing an iterative approach, both parameters are adjusted until they match 22 year mean values of the NASA Surface meteorology and Solar Energy (SSE) mission [42], which are queried online by LAT / LON coordinates for each simulation run, allowing a worldwide application of the tool with sufficient result quality.

The diffuse irradiation and the SVF are computed using a simplified approximation of the sky dome with points, where each point represents a spherical segment. The azimut (orientation) and zenit (height) angle distance between the points and the azimut angle offset between individual zenit angle layers can be configured enabling the creation of a hemisphere, where each point represents the same fraction of the area, which produces the best results according to Zahn [66]. Moreover, hemispheres with variable point density can be created to adapt to performance and quality requirements of the given use case. To compute the radiation power of the hemisphere points the Standard Overcast Sky (SOC) model according to Fu and Rich [15] is used. Analog to the sun points, the hemisphere points are created in a 100 000 km radius around the observation point as point features in the 3DCityDB with their radiation power as an attribute.

For the creation of a computational basis on roofs and facades a regular point grid is placed on the building surfaces. Each point represents the same fraction of the area of the building surface which is determined by averaging. The points are used as reference points for the estimation of the solar irradiation and are stored in the 3DCityDB with the inclination and orientation of the surface they belong to as attributes. Considering performance and quality criteria the density of the point grid can be configured. To prevent the points from intersecting the surface they are placed on during the ray tracing, the point grid is created with a small offset (5 cm to 20 cm) in direction of the surface normal. As this slightly increases the field of vision, rays with a incidence angle smaller than 0° according to Eqn. 1 have to be filtered, depending on the position of the sun and the inclination and orientation of the surface.

$$AngIn_{\theta,\alpha} = \arccos\left(\cos(\theta)\cdot\cos(G_z)+\sin(\theta)\cdot\sin(G_z)\cdot\cos(\alpha-G_a)\right) \quad (1)$$

The shadows cast by the surrounding constructions are considered by performing a visibility analysis applying a ray tracing approach. For each building point rays to all sun and hemisphere points are created which are tested for intersection with building geometries and the DTM using a ray / triangle intersection test according to Möller & Trumbore [41]. Therefore, all building geometries are triangulated using the Java3D library [45] in advance. The resulting triangles are stored in a bounding volume octree index structure significantly decreasing the number of expensive intersection tests. Both ray creation and intersection test are implemented using a thread pool allowing to process several surfaces in parallel to increase scalability. The influence of the visibility analysis can be observed in Fig. 4. Points in narrow corners and close to the ground receive less irradiation than points at roof tops or at unobstructed walls.

For the processing of large models (e.g. whole cities) a tiling strategy has been implemented. The simulation domain is split into cells with an edge length, that can be defined in the configuration. Each cells is loaded individually for processing to avoid memory leaks. For the visibility analysis the cell, that is currently being evaluated and its eight neighbor cells are included.

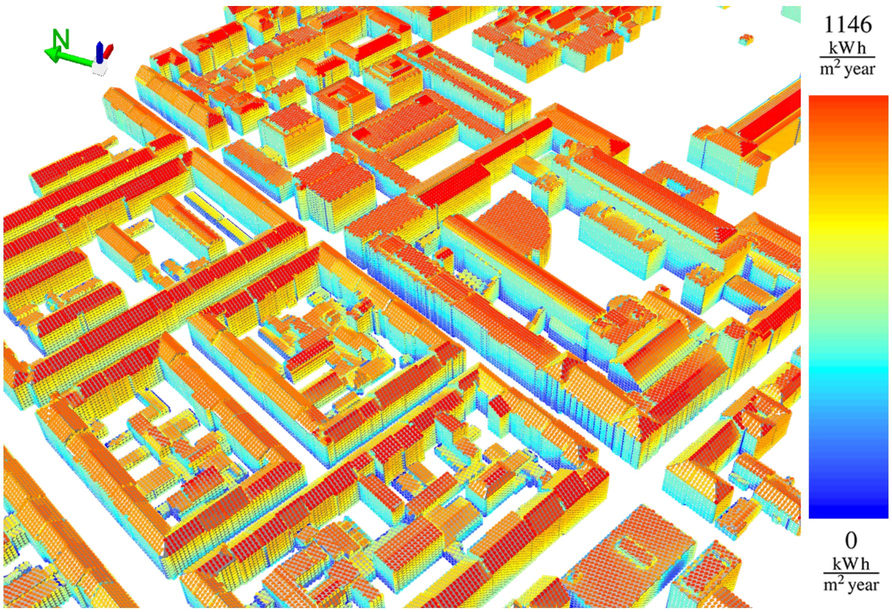

Fig. 4 Yearly irradiation sum (kWh/m^2/year) for building points at the TUM campus and surrounding buildings.

4.2 Results

The output estimates of the application are the direct, diffuse and global irradiation energy values and the SVF. All of them are presented in different spatial and temporal aggregation levels. First, all results are computed for each building point by summing up the values for direct and diffuse irradiation and the fraction of the area of the hemisphere respectively for each non intersected ray. The results per point are aggregated per month (kWh/m^{2}month) and are written to a new database table in the 3DCityDB. They can now be evaluated based on spatial and attributive criteria using Structured Query Language (SQL). The global irradiation is calculated by summing up direct and diffuse irradiation. An example of the yearly sum of the global irradiation per point is shown in Fig. 4.

Besides the point results, aggregates for each building surface and building are computed in monthly (kWh/month) and yearly (kWh/year) time resolution using the Java 8 Streams API for parallelization [58]. Therefore, the results per point are summed up for each surface or building respectively. The aggregated parameters are stored in the city model with the features they belong to using the Generic Attributes extension mechanism of the CityGML standard. Thus, they are available for visualization and analysis tools of the CityGML framework. The thematic surface and building instances of the city model are *persistently semantically enriched* with the results of the solar potential analysis allowing for data fusion with other information like the energy demand estimation describes in Sect. 6 increasing the utility value of the city model.

4.3 Evaluation and Discussion

For the accuracy evaluation of the method two solar potential analysis have been conducted based on the CityGML city models for Weihenstephan near Munich and Potsdam. As part of a Bachelor's Thesis by Benjamin Eberle [13] their results have been compared to ground truth data series from pyranometers by Deutscher Wetter Dienst (DWD) ranging from 1983 to 2005 having a maximum measurement inaccuracy of $\leq \pm 5\,\%$ for an hourly and monthly temporal resolution.

The monthly resolution shows relatively low deviations between measured and estimated solar irradiation. The direct irradiation is overestimated during winter and underestimated during summer, resulting in an absolute underestimation of the global irradiation sum per year of $\sim$25 kWh/m^2/year for both test cases which corresponds to a relative deviation of less than $\sim$3 %. Comparing the NASA data to the DWD data has shown, that these deviations correlate with the deviations of the transition model compared to the DWD data. Hence, they are likely caused by the calibration of the transition model with the NASA data. A calibration of the transition model with high quality data from ground measurements could further improve the accuracy of the model.

The comparison of the hourly resolution between DWD and transition model shows significant deviations. Generally, the solar irradiation is underestimated in the morning and evening and overestimated at noon. Those inaccuracies are caused by an incorrect calculation of the relative optical path length ($m(\theta)$), especially for low sun positions with a zenit angle (θ) of more than 80°, as Eberle found in his study [13]. Hence, the transition model does currently not deliver accurate estimates for a temporal resolution of one hour, in contrast to daily, monthly or yearly aggregated values. A model including correction factors for the refraction of the sunlight for low sun positions could help to increase the quality of the results.

Another factor influencing the quality of the solar irradiation estimation is related to the current practice of data acquisition for 3D city models. Today, most models are derived in automated processes from Light Detection And Ranging (LiDAR) point clouds and official geographic base data using predefined roof shapes. The application of these roof shapes may cause a slight change of roof inclinations, which can strongly influence the amount of radiation power a surface receives. Additionally, installations and building infrastructure on roofs and facades are not included in the model, which decrease the usable area for solar energy generation significantly.

The approach for the estimation of solar irradiation based on CityGML city models described in this section delivers reliable results for a wide range of applications. It can be applied to models of arbitrary size. In a test scenario, the roofs of the CityGML model of the London Borough of Barking and Dagenham containing $\sim$89 000 buildings have been calculated successfully. The work of Kausika et al. [28] presents a case study for the city of Utrecht, Netherlands where the tool has been used to support decision making in the planning of the cities new railway station. The simulation can be controlled with a Graphical User Interface (GUI) and the results can be visualized and analyzed using a cloud-based 3D web client [64, 65]. This enables non expert users to perform, visualize and evaluate the sun potential analysis.

5 Simulation of detonations in urban space based on semantic 3D city models

The second detailed usage example introduced in this section is about the simulation of explosions in urban space using a semantic 3D city model as data exchange platform. The following summary is based on the results published in Willenborg et al. 2016 [62].

5.1 Introduction

Urban regions are characterized by dense population and a high concentration of infrastructure and businesses. Thus, they are highly vulnerable to destructive events cause by humans or nature. One of the most threatening scenarios endangering those regions are explosions caused by catastrophic events, accidents, or terrorism. Computational Fluid Dynamics (CFD) simulation tools support planning and decision making in the field of explosive safety and building construction and allow strategic and conceptual preparation for individual blast scenarios [56]. These applications are tailored to efficient simulation of explosions and blast waves, but do not provide interactive access to simulation results. 3D city models and their frameworks offer comprehensive tools for visualization and result analysis even for non-expert users. They represent a reliable and growingly available data source for both geometries and semantics in an urban context.

When trying to perform CFD simulations based on semantic 3D city models we encounter two substantially different modeling paradigms: 3D city models, on the one hand, are modeled *object based*. According to the ISO 19109 definition of geographic objects [24], the city model objects are decomposed following logical criteria which can be observed in the real world. Their shape, orientation and location in the model is derived from their real world counterpart. CFD simulation tools on the other hand, operate on *field-based* models. The simulation domain is subdivided into e.g. a regular grid of finite volume elements or volume pixels (voxels). Real world objects are approximated by an accumulation of these cells.

The central challenge is to allow information exchange between both models and to develop an automated workflow that allows non-expert users to configure, perform, visualize and analyze blast simulations based on semantic 3D city models according to the international standard City Geography Markup Language (CityGML). An example of the desired information flow is given in Fig. 5. A field-based representation of the city objects needs to be derived that allows the usage of the semantic information of the city model for the simulation and the back-referencing of the simulation results to their corresponding city model entities.

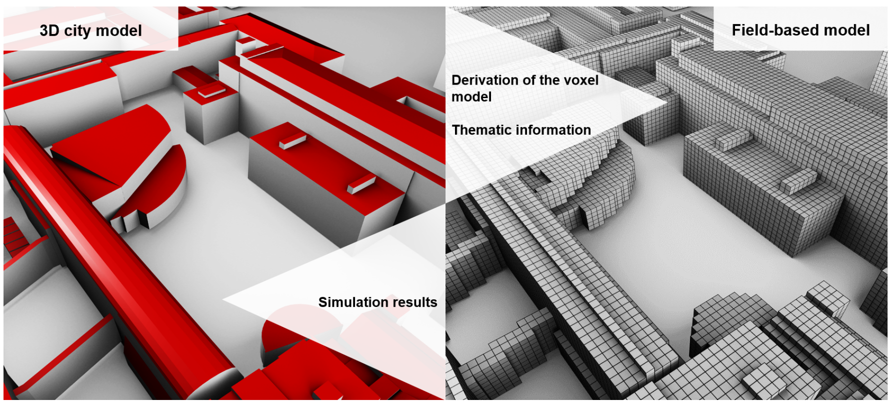

Fig. 5 Information exchange between the semantic 3D city model and the voxel representation of the simulation tool.

5.2 Derivation of a voxel model from CityGML geometries

The derivation of the voxel representation from CityGML city models is performed using the Open Source 3D geodatabase 3DCityDB running on a PostgreSQL/PostGIS installation. The process is implemented as Procedural Language-/PostgreSQL (PL/pgSQL) database functions, hence only lightweight function calls have to be transfered between the main application and the database. User interaction and workflow control is implemented in Java as a plugin for the 3DCityDB Importer/Exporter. The application comes with an easy-to-use Graphical User Interface (GUI), where all required configuration can be handled interactively. For the derivation of the voxel model the desired CityGML layers and the simulation domain as a Bounding Box (BBox) need to be selected. Furthermore, the edge length of the voxels needs to be specified. This parameter is crucial for the performance of the application and should be adjusted depending on the quality requirements of the scenario.

The voxel model is computed in two steps. First, the voxels located in the simulation domain need to be created. Therefore, the observed area is divided into a regular grid according to the voxel edge length, starting from its lower left bottom. The resulting integer IJK coordinate system for the grid cells can now be used for the voxel creation. Based on the origin of the grid, the voxel edge length and the grid coordinates a PL/pgSQL functions creates all voxels in the domain as Post Geographical Information System (PostGIS) spatial objects of type PolyhedalSurfaceZ in the Coordinate Reference System (CRS) of the city model using PostGIS spatial operations. Second, each voxel is queried for spatial relation with the city model objects using the PostGIS 3D intersection test procedure. Thereby, the GiST index structures provided by the database system are used [20]. They implement an R-Tree spatial index which increases query performance using a tree data structure for bounding box comparisons [19]. All voxels having a spatial relation to a city object are added to the field-based representation. An example of a voxel model derived from a CityGML model of the campus of the Technical University of Munich is illustrated in Fig. 5.

5.3 Information exchange between city and voxel model

Besides its geometric representation, for each voxel overlapping a CityGML geometry its logical reference to the intersecting city model object is stored in the database, where a voxel is uniquely identified by its grid coordinates and a CityGML object by its GMLID. The resulting n:m relationship between voxels and city model objects can be used to exchange information between both systems using standard database join operations.

Fig. 6 shows an illustration of a CityGML building consisting of four WallSurface, two RoofSurface and one GroundSurface objects, its overlain voxel representation and the logical links between both of them. The semantic information (e.g. material, color, area) attached to the highlighted WallSurface W4 is linked to the highlighted voxels and can be utilized by the simulation tool. The other way round, results delivered by the simulation software in the field based model (e.g. highlighted voxels) can be referenced to their corresponding city objects (e.g. WallSurface W4).

Consequently, simulation results can be aggregated per city model object. Using the Generic Attributes extension mechanism of the CityGML standard the simulation results can be stored with their corresponding objects in the city model. The *persistent semantical enrichment* of the city model objects makes the simulation results available for visualization and analysis tools of the CityGML framework. Moreover, the information generated by the simulation can be combined with other data enhancing the analytic capabilities of the model and therefore increases its value.

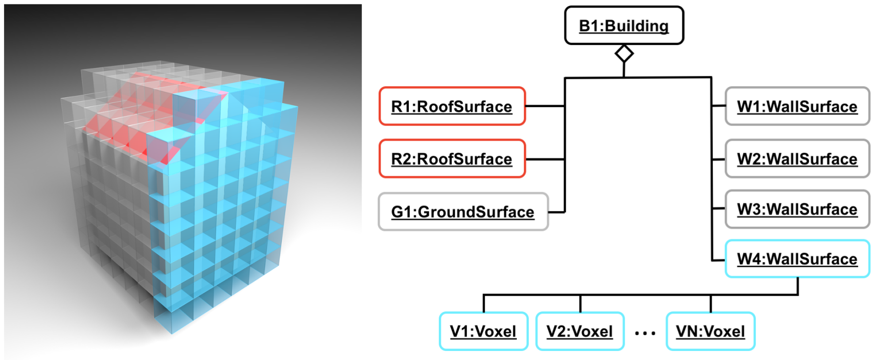

Fig. 6 Field based voxel approximation of an object based CityGML building. The logical relations between WallSurface W4 and the voxel model are highlighted in blue color.

5.4 Example usage scenario: Blast simulation with the Apollo Blastsimulator

In the following section the proposed approach for the integration of CFD simulation tools and 3D city models is evaluated for the example of a blast simulation with the *APOLLO Blastsimulator*. The work described in this section is based on the Master's Thesis of Willenborg [61]. The Apollo Blastsimulator is a CFD simulation tool developed at Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institute (EMI) in Freiburg, Germany. It is mainly used for risk analysis and combines good usability, versatility and computational efficiency by tailoring the methodological concepts to the application of explosions and blast waves [32].

For evaluation purpose a fictive test scenario has been created. We assume, that an unexploded bomb from World War II has been uncovered during ground working in the inner court of the Technical University of Munich. Only the CityGML building layer has been used, all buildings have been translated to a plane.

First, the computational mesh the Apollo Blastsimulator operates on needs to be generated with the method described above. It is passed to the application in the form of a text file. After a simulation run, the Apollo Blastsimulator returns two types of results. Besides physical quantities (e.g. overpressure, overpressure impulse) a set of probability values for various damage categories (e.g. glass, masonry or concrete wall, eardrum damage, lethality) is provided. Using the logical link between the voxel and the city model the simulation results are aggregated and stored as Generic Attributes with the wall- and roof surface objects in the city model.

Visualization and analysis tasks can now be performed with the cloud-based 3D web client developed at the Chair of Geoinformatics of the Technical University of Munich. The browser based application uses the Cesium Virtual Globe Viewer to visualize the 3D city model using state of the art WebGL technology for rendering and the glTF format for exchanging 3D visualization files [64]. The well known interface of the 3D globe allows intuitive navigation and exploration of city models. Thematic information is distributed via cloud services like Google Spreadsheet$^{\text{TM}}$ or Google Fusion Tables$^{\text{TM}}$, that allow analytic tasks with spreadsheet calculations.

To demonstrate the analytic capabilities of the 3D web client we will identify all walls, where windows are likely to break if the bomb cannot be defused and needs to be detonated on site. First, we need to setup the query in the attribute panel of the web client. As shown in Fig. 7, we enter the required filter criteria to query only wall surfaces with a maximum glass breakage probability of $>70\,\%$ (see enlarged entries). After issuing the query, all matching surfaces are highlighted (yellow) in the 3D view. Further analytic tasks on the selected objects can be performed directly in the client with its aggregation operations. For example, by summing up the area of all currently selected surfaces we are able to determine the total affected wall surface area. By multiplication with factors for window area per wall and window price we can perform a rough cost estimation for broken windows.

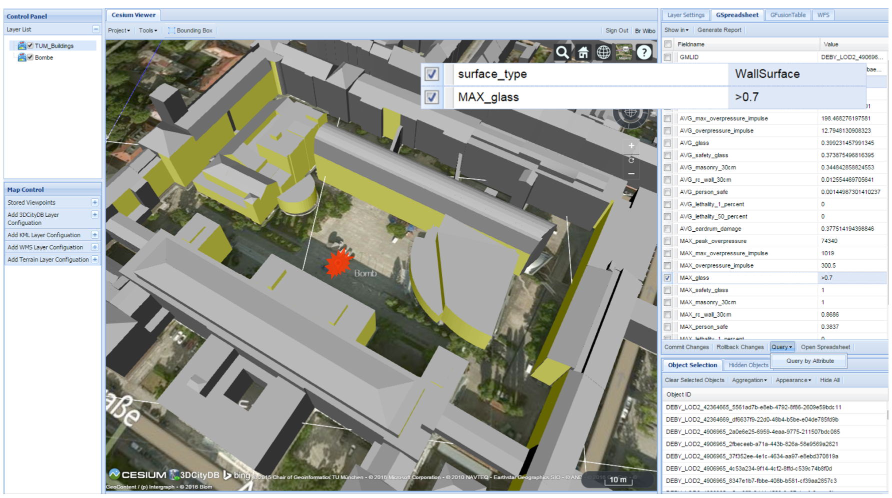

Fig. 7 Evaluation of a fictive blast scenario on the campus of the Technical University of Munich with the cloud-based 3D web client: Wall surfaces with a glass breakage probability $>70\,\%$ are highlighted in yellow color in the 3D view.

6 Estimation of building heat energy demands

In Sec. 4 the importance of energy policies in the context of CO_2 saving potential was discussed. An essential component of the global energy demand, which is responsible for a huge amount of emitted CO_2, is required for the heating of living spaces. The goal is to reduce the energy demand by appropriate planning actions and, thus, to reduce the emission of greenhouse gases. To initiate these actions in terms of optimization and refurbishment of residential buildings and to frame political funding instruments it is essential to simulate the current and future energy demand, so it is possible to virtually play through different scenarios and compare their impacts on the build environment. In Kaden et al. [26, 27] the authors have shown that virtual semantic 3D city models combined with other data from official statistics serve as an ideal information base to support the calculation of heating, electricity, and hot water energy demands. The following summary is based on these publications. The calculation of heating energy demand of residential buildings is presented

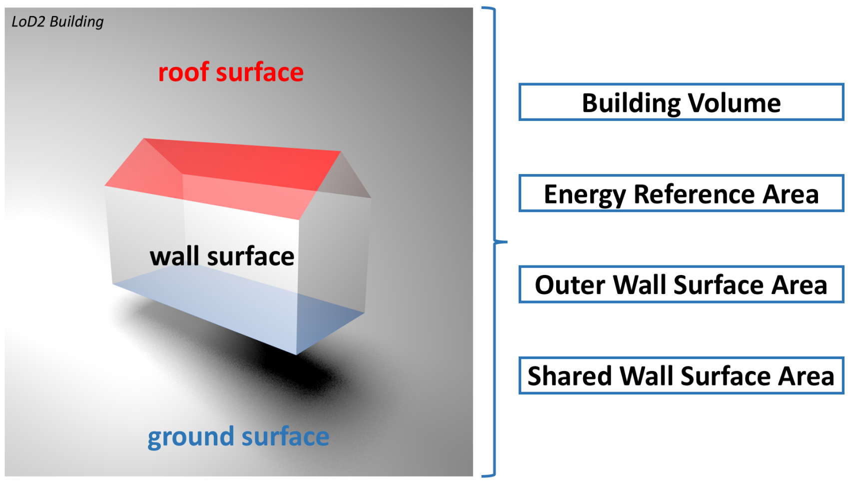

Fig. 8 Relation between building characteristics and required parameter for heat energy demand estimation.

and the added value of semantic 3D city models is shown. The current German Energy Saving Regulation envisages the building simulation methods according to DIN V 18599 [12] for calculating the heat energy demand of buildings. This standard specifies the method for calculating the monthly net, final, and primary energy demand for heating, cooling, ventilation, domestic hot water, and lighting. Besides information about the type of use of the buildings and their refurbishment state, especially information on the building geometry and building construction are crucial for the calculation of heat energy demands. By component-related calculations, it is possible to identify saving potentials of refurbishment measures.

Fig. 8 illustrates the coherence between the geometric properties of the virtual building models and the input values needed for the energy demand estimation. On the left of the figure a building is shown in City Geography Markup Language (CityGML) Level of Detail 2 (LoD2). The building is subdivided into its parts (roof surface, wall surface and ground surface). Thus, it is possible to meet the requirements of DIN V 18599 [12] to use it for a component-related calculation. On the right side of the figure the main parameters that can be calculated based on the geometric and semantic representation of the building are listed. Besides the building volume the energy reference area can be calculated using the ground surface area and the number of full stories. The shared wall surface area is a significant parameter for calculating the heat energy demands of buildings. Heat losses through walls require a drop of temperature from the inside to the outside of the building. The shared wall surface area is the portion of the total wall surface area that is adjacent to another surface that belongs to a heated building or building part and, thus, is not affected by heat losses. This ratio can be calculated using the topology of the virtual 3D city model.

Information on the building construction and the renovation state of a building are not officially provided by administration departments in Germany, thus this information has to be linked to the buildings by the integration of statistical information from statistics agencies. The heat transfer coefficients are determined based on the age class of a building. These coefficients can be adopted from the values of the predominant building type in each age class. It is however possible, if accurate values for the building parts are available, to use the precise values instead of the estimated values. Another important step towards more agile urban planning is the

Fig. 9 Virtually improving the energy efficiency of all buildings in a road according to the German Energy Saving Regulation 2009 using a cloud-based 3D web client.

ability to simulate planning scenarios. Fig. 9 depicts how the 3D city model can be used in combination with an interactive cloud-based 3D web client [64, 65] for the evaluation of refurbishment measures. The example shows all buildings in a street in Berlin, which have been previously selected by the attribute *street name*. To estimate the impact of an energetic refurbishment measure according to the Energy Saving Regulation 2009 we summed up the heating energy demand in kWh per year for all buildings. For the example in Fig. 9 the estimated total heat energy demand for all buildings is 11.38 GWh per year prior to the refurbishment measure. Adjusting the values of the heat transmission coefficients according to the requirements of the German Energy Saving Regulation 2009 (see step 2 in Fig. 9) triggers an immediate recalculation of the heat energy demand for each individual building. Summing up the heat energy demand values of all buildings in the street leads to a total estimated heat energy demand of 5.57 GWh per year. This corresponds to a reduction by half.

7 Discussion and outlook

This article provides a review of what 3D city models are and how especially semantic 3D city models contribute to a better understanding of the city as a complex system. After giving an overview on the current state of 3D city model applications and how their use cases can be categorized, three practical examples were described in detail, covering the estimation of solar irradiation, the simulation of detonations, and the estimation of building heating energy demand.

As demonstrated with these use cases, semantic 3D city model are an ideal integration platform for many kinds of applications around the city system supporting decision making and planning. They combine a detailed geometric representation of the real world with rich thematic information for the most common features of cities and rural areas. This facilitates the virtual mapping of complex processes of the city system that need to be comprehensible and predictable to maintain good living conditions in the urban area in the future.

As, delineated in Sec. 3, 3D city models are widely used today and there are many future applications to come. Recent advances in augmented and virtual reality, the integration of Geographical Information System (GIS) and Building Information Modeling (BIM) and advances in procedural modeling appear as a promising sources for future use cases and applications [4].

However, semantic 3D city models need further developments for future challenges. Regarding the examples discussed in Sec. 4 and Sec. 5 a significant improvement would be the inclusion of dynamic attributes to enable the storage of the time dependent result data of the simulations directly within the city model. This issue is currently researched by Chaturvedi et al. [7].

The quality of 3D city model data available today is still an issue. A frequent problem for instance, is that the outer shell of volumetric city model geometries is not closed, avoiding sound volume computation, which is a relevant spatial operation for many applications (see Sec. 6). Research is done on that topic by e.g. Sindram et al. [51] and Steuer et al. [53].

Another important challenge in the context of complex city systems is the coupling of planning actions and the analysis of their effects. While Sindram et al. [50] are developing a model for describing planning actions, Elfouly et al. [14] are working on a framework for evaluating their effects on Key Performance Indicators (KPIs). To compare different scenarios Chaturvedi et al. [8] are currently working on a concept for the versioning of entire 3D city models that will, for instance, allow the comparison of different planning stages.

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