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Review

Applications of 3D City Models: State of the Art Review

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Abstract: In the last decades, 3D city models appear to have been predominantly used for visualisation; however, today they are being increasingly employed in a number of domains and for a large range of tasks beyond visualisation. In this paper, we seek to understand and document the state of the art regarding the utilisation of 3D city models across multiple domains based on a comprehensive literature study including hundreds of research papers, technical reports and online resources. A challenge in a study such as ours is that the ways in which 3D city models are used cannot be readily listed due to fuzziness, terminological ambiguity, unclear added-value of 3D geoinformation in some instances, and absence of technical information. To address this challenge, we delineate a hierarchical terminology (*spatial operations, use cases, applications*), and develop a theoretical reasoning to segment and categorise the diverse uses of 3D city models. Following this framework, we provide a list of identified use cases of 3D city models (with a description of each), and their applications. Our study demonstrates that 3D city models are employed in at least 29 use cases that are a part of more than 100 applications. The classified inventory could be useful for scientists as well as stakeholders in the geospatial industry, such as companies and national mapping agencies, as it may serve as a reference document to better position their operations, design product portfolios, and to better understand the market.

Keywords: 3D city models; 3D GIS; 3D geoinformation; use case; application; CityGML; LiDAR; urban models; 3D building models; GIScience

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1. Introduction

A 3D city model is a representation of an urban environment with a three-dimensional geometry of common urban objects and structures, with buildings as the most prominent feature [1–4]. A typical 3D city model is derived from various acquisition techniques, for instance, photogrammetry and laser scanning [5–8], extrusion from 2D footprints [9,10], synthetic aperture radar [11–15], architectural models and drawings [16–18], handheld devices [19,20], procedural modelling [21–26], and volunteered geoinformation [27–29]. Seemingly, visualisation dominated the early uses of 3D city models. However, as the technology developed, 3D city models have become valuable for several purposes beyond visualisation, and are utilised in a large number of domains [30–35] (Figure 1). Such diversity and the increasing number of applications render it difficult to keep track of the utilisation possibilities of 3D city models. It appears that, despite the near-ubiquitousness of 3D city models, a comprehensive inventory of 3D applications does not exist (examples of previous efforts are presented in Section 2). Because each 3D application requires its own specific 3D data, a comprehensive inventory can help linking the requirements to specific applications. Contributing to these efforts, as we do in this paper, helps identifying the requirements emerging across domains to generate 3D data that is fit-for-purpose. Such an inventory also provides a reference for user testing, thus contributes to identifying the eventual understanding of the models' fitness-for-use.

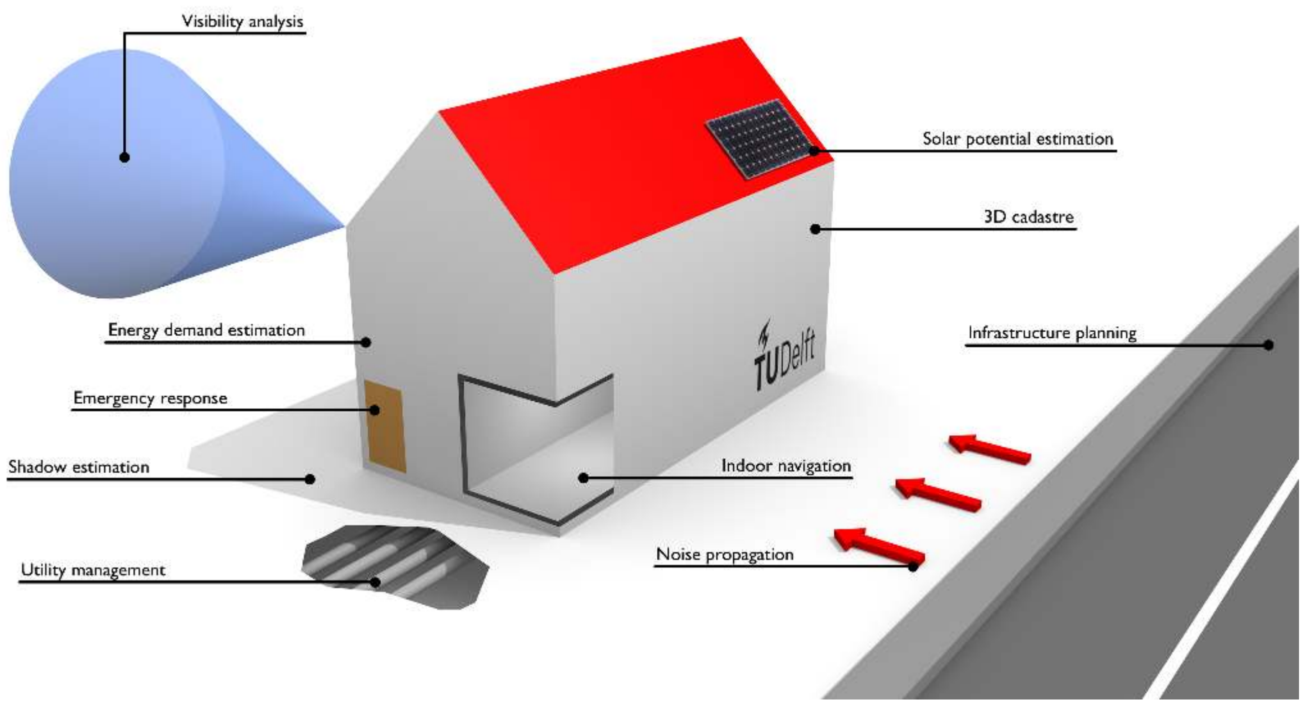

Figure 1. 3D city models may be applied in a multitude of application domains for environmental simulations and decision support.

In Section 3 we present the methodology of our survey, and discuss barriers we encountered. It is important to note that throughout this manuscript, we focus on the state of the art regarding the utilisation of 3D city models; however, we also use the terms 3D GIS and 3D geoinformation when the context warrants it. These two terms (3D GIS and 3D geoinformation) may cover a larger set of 3D information (e.g., terrain, abstract 3D plots, *etc.*); however, in the context of this paper, our narrow focus is on 3D city models and these terms also refer to software or data environments in which one finds 3D city models. An important challenge in deriving an inventory of how 3D city models are utilised is the fuzziness in the segmentation and terminology (e.g., use cases, applications; or 3D city model, 3D geoinformation, 3D GIS, *etc.*). Many terms appear to be used often interchangeably in literature. We attempt to solve this terminology issue in this paper by proposing a hierarchical framework and criteria we developed based on our subjective reasoning. Finally, in Section 4, we give a comprehensive list of use cases, as a classified list with descriptions and references.

2. Related Work

Publications in the 3D GIS domain regularly list various uses of 3D geoinformation as examples [36–39]. However, most of these lists are brief, specific to the paper's focus, and are not necessarily always supported with references. In the past 15 years, only a few researchers have focused on the general applicability of 3D geoinformation for solving industrial and research problems. In a 2000 study, Batty *et al.* [40] provide a conceptual study on the use of 3D city models, focused on visualisation and spatial planning. They have segmented the use of 3D city models into 12 categories of industries: emergency services, urban planning, telecommunications, architecture, facilities and utilities management, marketing and economic development, property analysis, tourism and entertainment, e-commerce, environment, education and learning, and city portals. Their list serves as an excellent starting point to re-examine after 15 years.

Ross [41] lists several applications and provides a general taxonomy of 3D use cases: (1) applications that are based only on geometry (e.g., estimation of the shadow); (2) analyses based on geometry and semantic information (e.g., estimation of the solar potential); and (3) analyses based on domain specific extensions and external data (e.g., noise emission calculation). While this approach provides a straightforward classification, the categories are not mutually exclusive in all cases, *i.e.*, we have encountered applications that would fit into more than one category. For instance, the estimation of the propagation of noise in urban environments requires only the geometry of buildings. However, if the geometries are supplemented with semantic information (e.g., material of the building and number of inhabitants), this could lead to an important improvement of the predictions (e.g., more accurate and precise model of the noise propagation), and a better assessment of the consequences of the noise.

Apart from the two taxonomy-oriented studies cited above, the conclusions from the 3D pilot project in The Netherlands [42–45] provide a valuable resource for this research. This recent collaboration comprised 65 geospatial stakeholders in The Netherlands and aimed at pushing national 3D developments forward. As a part of this project, several use cases have been critically investigated with their applicability in The Netherlands in order to find prominent, exemplary 3D use cases. In a more recent study conducted in 2015, Wong [46] investigates the economic value of 3D geoinformation as an initiative of the EuroSDR 3D Special Interest Group [47]. A part of the work deals with several examples of uses of 3D GIS, which are classified based on areas (domains) and applications. An area (e.g., health) may contain multiple applications (e.g., emergency services, epidemiology). Many references from this recently compiled list have been incorporated in our research. The same goes for other related studies, including ones which are mostly focused on 2.5D data or point clouds [48–51].

Furthermore, various publications focus on the *applicability* of 3D city models in a certain discipline. For instance, Zhang and Zhu [52] and Chen [53] investigate the applications of 3D city models to urban design.

Finally, while most researchers appear to take theoretical approaches towards the applicability of 3D; there are various empirical studies related to the usability of 3D, especially in the visualisation domain. These studies are motivated by the fact that 3D visualisations can suffer from perceptual issues such as occlusion and perspective changes, *i.e.*, because the scale is not uniform over the view, judging distances becomes harder (e.g., [54]). Current understanding of the usability of 3D visualisations based on empirical evidence is that for some tasks, using 3D may hurt performance, *i.e.*, people perform better with 2D alternatives (e.g., [55]), where in some cases, the performance appears to be similar (e.g., [56]), and in some others, 3D appears to be appropriate to use (e.g., [57]). In most cases (however not in all cases) where 3D is compared to 2D, if asked, participants appear to prefer 3D. This preference, especially when combined with the lack of evidence that it is the better solution, is termed naive realism ([58]), or naive cartography ([59]). While we believe that it is important to be aware of research that accounts for human perception and cognition, in this study, we take a literature review approach and elaborate on the utilisation of 3D models as reported those who use it and for the purpose they report using it; eventually inferring categories of reported use.

3. Methodology

The main methodology in this paper is a literature review and a synthesis. We screen scientific literature, project reports as well as online resources on 3D geoinformation science with a focus on the utilisation of 3D city models in a comprehensive and systematic manner (Section 3.1). During our screening and review process, we have encountered a number of issues that needed to be addressed. First, terms such as 'use case' are somewhat ambiguous in GIS-related documents, and it was not immediately clear how to delineate different uses of 3D. To address this challenge, we developed our own definitions: our terminology and approach can be seen in Section 3.2. A second issue was that in several use cases it was unclear in the documents what kind of spatial data was used, and the benefit of 3D city models was questionable. In Section 3.3 we present a set of criteria that each use case had to fulfil in order to be included in our inventory. Third, classifying use cases into meaningful groups was a challenge caused by lack of documentation, overlap of uses, and unclear role 3D city models have in some. In Section 3.4 we present our classification along with a review on other approaches that at first sight appear to be credible, but that, after studying them closely, we deemed not suitable.

3.1. Principal Sources of Our Survey

We have carried out a systematic survey of documents related to the application of 3D city models. Besides related work (Section 2), we have browsed through issues of several journals in the GIS field and conference proceedings in the last two decades (for the selection of authoritative GIS journals we have considered lists such as the one found in Biljecki [60]). As a part of our work, we have also been in an informal contact with stakeholders, such as municipalities and local governments, who have informed us about a few applications of 3D city models. Furthermore, a few companies provided publicly available brochures that list uses of 3D city models (e.g., [61]), which we have also taken into consideration. While they do not contain extensive information, such lists have served as a hint to search for more information.

In recent years, there have been a few events and initiatives dedicated to practical topics in 3D city modelling, which have resulted in reports. For instance, the aforementioned Dutch 3D pilot [44], but also the German initiative InGeoForum [62] and the European COST Action TU0801 [1,63], a research project that focused on different aspects of 3D city models. We have also examined the CityGML standard [64,65] since it contains some information about the intended uses of the data model. Documentation of datasets and data specifications usually lists the main intended applications [66–71], and those have been of help as well.

3.2. Terminology and Segmentation

From our inventory we can conclude that there are many undefined terms surrounding the utilisation of spatial data: use cases, applications, operations, uses, and so on. A fuzzy terminology prevents an unambiguous organisation of purposes of 3D geoinformation.

The term *use case* has been defined in software engineering as a sequence of actions that provide an objective or subjective value to a user [72]. We second this definition: applied to GIS and 3D city modelling, a use case can be seen as a meaningful set of spatial operations that accomplish a goal a user wants to achieve with a spatial data set. In this paper, we view the use cases from the perspective that the user can *technically* arrive at her or his goal (that is, perceptual and cognitive aspects are not considered in this paper). The use case is tied to a specific discipline (an industry or sphere of activity and knowledge) to which it may provide a substantial benefit. We infer the benefit based on the documented cases that people actually use the 3D city models in practice; this indicates to us that they at least see a subjective benefit in using the 3D models.

Following this definition, when a use case is employed in the context of a specific domain (e.g., archaeology) to solve an application problem we define an *application*. For instance, the computation of the volume of a building is a spatial operation that is, among other operations, used in at least two use cases: estimating the energy demand (larger buildings require more energy to be heated) [73], and estimating the number of inhabitants of a building (larger buildings generally host more people) [74]. The latter use case is valuable in at least two application domains: for emergency response (estimating the number of people that have to be evacuated), and in environmental modelling (estimating the number of people affected by noise). Another example is the estimation of shadows cast by buildings on the surrounding area. This use case may be employed in adjusting the estimations of the solar potential of rooftops, but also in urban planning to assess whether a planned building, if built, would threaten their neighbours' access to sunlight.

Figure 2 shows an example of the described terms, and of their overlap. In this paper we focus on listing use cases, but we give importance to applications for a better understanding of use cases. Furthermore, as it will become evident from the list, some use cases have fuzzy boundaries, so a degree of subjectivity and personal choice has to be accepted by the reader.

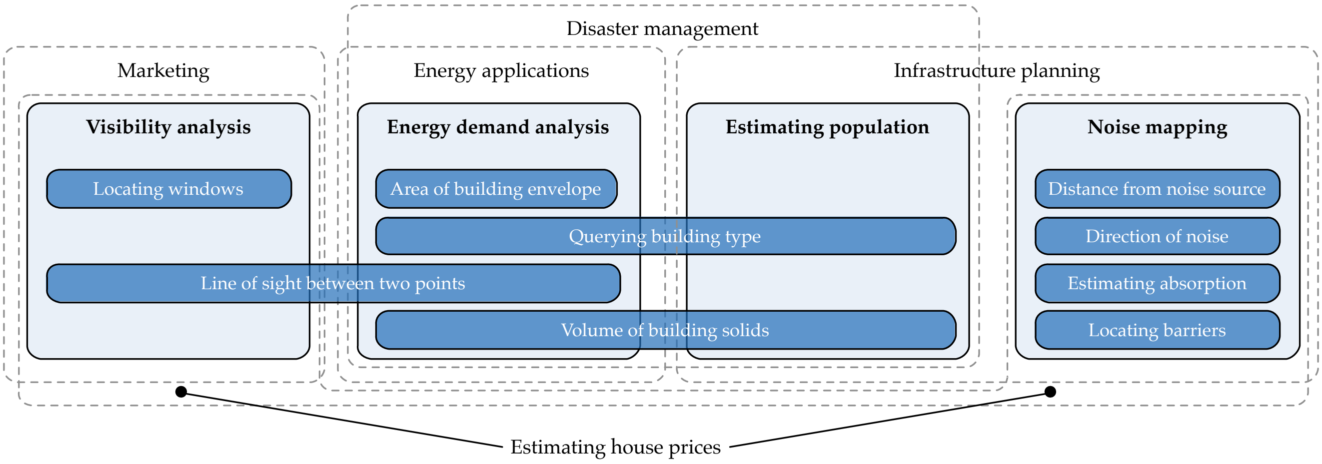

Figure 2. The tangled relations between spatial operations (dark blue), use cases (light blue) and applications (outlined with a dashed stroke), and their overlap which prevents a straightforward listing and classification. This example is simplified, as the application domains normally have more corresponding use cases, and use cases usually consist of more than a few spatial operations.

3.3. Criteria for the Inclusion

3.3.1. Granularity and Forms of the Data

Because 3D city models are ambiguously defined as 3D representations of the urban environment, technically this may include also 2.5D data sets, such as coarse digital elevation models (DEMs) with no buildings and other urban features. A confusion in the terminology is also evident in the large number of papers that claim to use 3D GIS, but it turns out that 2.5D data has been used (e.g., [75]).

In this research, we consider 3D representations that contain buildings and other relevant urban features. Therefore DEM-only analyses containing no buildings and other distinct city objects are not considered. In our survey we focus on 3D city models containing boundary representations, but we also include use cases that are documented to use dense LiDAR point clouds in which buildings are distinguishable, and for which 3D city models could also be used.

On the other hand, we exclude applications focused explicitly on indoor of individual buildings, as they are numerous and it is difficult to distinguish which of them fall into Building Information Modelling (BIM) and which in GIS domain.

3.3.2. Added Value of 3D Data

In theory, all 2D and 2.5D GIS use cases are possible with 3D GIS data as well, but that does not necessarily make them 3D GIS use cases. Hence, in our research we include only use cases that have a clear benefit from 3D geo-data:

- use cases that are only possible with 3D city models as defined in the previous section, and
- use cases that are possible with 2(.5)D GIS data, but that are significantly improved when 3D data is used (e.g., increased accuracy, more applications). For instance, de Kluijver and Stoter [76]

present a method to estimate the propagation of noise in urban environment from 2D data. In a subsequent paper, Stoter *et al.* [77] use 3D city models for the same purpose, providing a clear improvement in the estimation. While this use case is possible with 2D data, using 3D models adds a substantial increase in the accuracy of the results and their interpretation.

Our experience is that some resources generously list applications that have an unclear or questionable usefulness of 3D city models, for instance, a 3D application in local law enforcement. We have made an attempt to investigate the exact role and added value of 3D city models in such applications, and when we did not succeed we left them out of our survey.

In this context, it is important to note the research of Herbert and Chen [78] who have investigated the added value of 3D data to 2D data in urban planning, and compared the benefit of 3D data. They have found that in this application 3D has advantages over 2D. Unfortunately, such research papers and information are rare.

3.3.3. Limit on the Usefulness, and Minor or Potential Use Cases

Some papers speculate about the value of 3D city models or list unrealised ideas for the utilisation of 3D city models that are not found elsewhere in literature and which do not appear to have been realised.

Another uncertainty is the potential use of 3D city models in certain application domains. Such have not been documented yet, but they appear to be likely used in the future. For instance, noise at a location of a house is one of the environmental externalities in house price models since it may negatively affect the value of real estate [79–81]. The estimation of the magnitude of noise at position in urban environment is a use case that predicts information without on-site surveys, and it can be integrated as a factor in estimation of the prices of real estate. However, we have not encountered this potential application being actually used.

Because of the questionable usability, and because we were not able to verify the claims, we have decided to exclude such use cases and applications from our survey. Instead we only include use cases that have been actually been practised.

3.4. Taxonomy of Use Cases

As noted in related work (Section 2), others have made categorisations of uses of 3D GIS data, but they are not similar to our work in their core. For instance, the taxonomy of Batty *et al.* [40] that was mentioned in Section 2 is oriented towards application domains (e.g., tourism), rather than use cases. We avoid delineating application domains since that would entail developing an additional taxonomy. We have looked into a categorisation that is both mutually exclusive (a use case should belong to only one category) and collectively exhaustive (categories should cover all use cases). However, only one criteria has convinced us to be suitable: the visualisation aspect. Therefore we categorise use cases into two groups:

1. Non-visualisation use cases, which do not require visualising the 3D models and the results of the 3D spatial operations. That is, the outcome of the spatial operation(s) can be stored in a database, e.g., solar potential of a roof surface, without the need of being visualised. The results *can be*

visualised, but that is not *essential* to achieve the purpose of the use case, and it is not essential to visualise it in 3D (e.g., we can show the calculated information using color density instead).

2. Visualisation-based use cases. This includes:
   - Use cases that require running computations as in the group 1., but where visualisation is very important and the use cases would not make much sense without it (e.g., navigation, serious gaming, and urban planning).
   - Visualisation-only use cases such as communication of urban information and virtual reality, which do not necessarily rely on spatial operations, but where 3D city models have been found as an important component. Note that we do not have empirical evidence, nor do we survey empirical studies in this paper. Therefore, we do not contend that these are best suited to be visualised in 3D; rather, we document that they *are* currently visualised in 3D in the body of literature we have surveyed.

Below we give a description of the previous attempts to develop a taxonomy in order to give an impression about the challenge of developing a classification of use cases, and to reinforce our approach.

By semantics and/or required attributes For example, distinguishing use cases on the criteria whether on top of the geometry semantics is required. This is similar to the approach of Ross [41], and the reason why it cannot be used is discussed in Section 2.

By the required minimum level of detail 3D city models are characterised by the level of detail (LOD), a measure that indicates their grade and scale [82,83]. The LOD implies the intended scope of use of 3D geoinformation and some use cases require datasets of a certain minimum LOD to be usable [84–86]. However, this classification is not a good idea for following reasons: (1) papers commonly do not give a focus on the LOD that was used in the analysis nor what would be the minimum required LOD; (2) the documented uses of LODs can be quite dispersed—we have encountered use cases that are used both with simple block models and architecturally detailed models containing interior (e.g., for determining the volumetric visibility); and (3) the performance of use cases is rarely investigated LOD-wise [87].

By the level of spatial granularity The uses of 3D data might be grouped by the spatial extent of the object of interest (e.g., city and neighbourhood level—see the classification of Richter *et al.* [88]). This approach falls short because there is too much variation within a use case. For instance, the estimation of the solar potential can be performed on one building only but also on all buildings in a city.

By the spatio-semantic coherence CityGML is well-known for its spatio-semantic approach to urban features [89], however, 3D city models may include polygon meshes where buildings, roads, and other urban features are not separable. This might not be relevant for use cases such as computational fluid dynamics and the estimation of the radio-wave propagation, but it is vital for use cases related to energy.

We reject this criteria because, similarly to the other described principles, there is too much overlap within the use cases. For instance, estimating the insolation of buildings is usually done on semantic 3D city models in order to relate the estimated values to each building. However, this may not be important for applications such as the urban thermal comfort where the insolation may also be estimated for each triangle in the polygon mesh where all the urban features are considered together.

By the nature of the output of the use case Another potential way to distinguish between use cases would be by their output: quantitative or non-quantitative. For instance, using 3D city models to estimate the floorspace results in an quantitative result in m^2 [90], but using 3D city models to enhance the navigation experience cannot be quantified in such an unambiguous way. The reason why we have decided to exclude this criteria is again fuzziness: for instance, urban planners use 3D city models to analyse shadows cast by buildings, which can be quantified (e.g., area of the shadow cast on the ground in m^2 or the shaded volume in m^3 [87]), however, our impression is that urban planners do not quantify it.

By the texture Use cases in which visualisation plays an important role considerably benefit from textures. This is an interesting criteria, but we have not found a convincing separation between use cases. In many use cases textures add some value, but they are not essential and there is no research on the performance of textures towards the quality of the utilisation. Recent research even indicates that the role of textures in 3D city models may be overestimated [91].

4. List and Description of Use Cases of 3D City Models

Based on the methodology in Section 3, we have identified 29 distinct use cases used in several application domains. We describe and list the identified use cases in no particular order, but we present them in two groups, as discussed in Section 3.4. For the few use cases which we could find information only from the web, we have provided the URL as a reference. At the end of the section, Table 1 gives the list of use cases.

4.1. Non-Visualisation Use Cases

4.1.1. Estimation of the Solar Irradiation

The estimation of the insolation of buildings is arguably one of the most prominent use case in 3D city modelling [84]. It is a mature topic in GIS initially conducted on digital surface models (e.g., [92]). However, the evolution of acquisition techniques and data models has enabled us to model buildings and their parts (e.g., roof), which has opened a door for multiple application domains requiring such granularity.

3D city models are used to estimate how much a building is exposed to the sun in order to assess the suitability of installing solar (photovoltaic) panels on roofs [93–105]. 3D city models provide geometric information such as the tilt, orientation and area of the roof, which are used as the main input for the solar empirical models [84]. Recent work has focused on extending the task for vertical façades, and taking into account the material of the receiving surface [106,107] (Figure 3).

Table 1. Overview of the documented use cases of 3D city models, divided into two groups: non-visualisation and visualisation use cases.

§	Use Case	Example of an Application
4.1.1	Estimation of the solar irradiation	Determining the suitability of a roof surface for installing photovoltaic panels
4.1.2	Energy demand estimation	Assessing the return of a building energy retrofit
4.1.3	Aiding positioning	Map matching
4.1.4	Determination of the floorspace	Valuation of buildings
4.1.5	Classifying building types	Semantic enrichment of data sets
4.2.1	Geo-visualisation and visualisation enhancement	Flight simulation
4.2.2	Visibility analysis	Finding the optimal location to place a surveillance camera
4.2.3	Estimation of shadows cast by urban features	Determination of solar envelopes
4.2.4	Estimation of the propagation of noise in an urban environment	Traffic planning
4.2.5	3D cadastre	Property registration
4.2.6	Visualisation for navigation	Navigation
4.2.7	Urban planning	Designing green areas
4.2.8	Visualisation for communication of urban information to citizenry	Virtual tours
4.2.9	Reconstruction of sunlight direction	Object recognition
4.2.10	Understanding SAR images	Interpretation of radar data
4.2.11	Facility management	Managing utilities
4.2.12	Automatic scaffold assembly	Civil engineering
4.2.13	Emergency response	Planning evacuation
4.2.14	Lighting simulations	Planning lighting of landmarks
4.2.15	Radio-wave propagation	Optimising radio infrastructure
4.2.16	Computational fluid dynamics	Predicting air quality
4.2.17	Estimating the population in an area	Crisis management
4.2.18	Routing	Understanding accessibility
4.2.19	Forecasting seismic damage	Insurance
4.2.20	Flooding	Mitigating damage to utility management
4.2.21	Change detection	Urban inventory
4.2.22	Volumetric density studies	Urban studies
4.2.23	Forest management	Predicting tree growth
4.2.24	Archaeology	Visualising ancient sites

Figure 3. Estimation of the solar irradiation of buildings for a specific date and time. In this case the surrounding vegetation and the type of the receiving material is also taken into account in the estimations. (Image courtesy of Argedor).

This application may benefit from attributes such as the address and type of building for additional analyses [108], and it is being supported by an increasing number of software implementations [109,110]. Furthermore, some researchers use dense point clouds rather than semantic 3D city models (e.g., [111–114]). For a comprehensive overview of research on solar potential applications see the recent review of Freitas *et al.* [115].

The estimation of the insolation of buildings is also vital to estimate the thermal comfort, *i.e.*, the detection of buildings that are exposed to too much sunlight, potentially resulting in overheating during summer [116,117]. This also allows us to design an urban layout to maximise the insolation of a neighbourhood [118], and to estimate the capacities of decentral energy sources in crisis management applications [119]. A further application is in the large-scale estimation of house prices. The information about the insolation can be used as one of the factors for estimating the property prices, under the assumption that solar radiation is capitalised in the value of a property [120]. Finally, 3D city models containing windows can be used to predict the indoor illumination [121,122].

4.1.2. Energy Demand Estimation

A use case that convincingly demonstrates the value of semantic 3D city models is the estimation of the energy demand of households (see Figure 4 for an example of the visualisation of the results of such analysis).

Recent years have seen the advent of this application, where researchers, predominantly in Germany, have used 3D city models to combine the data of the volume of buildings, number of floors, type of the building, and other characteristics to predict the energy demand for heating and/or cooling [73,123–134].

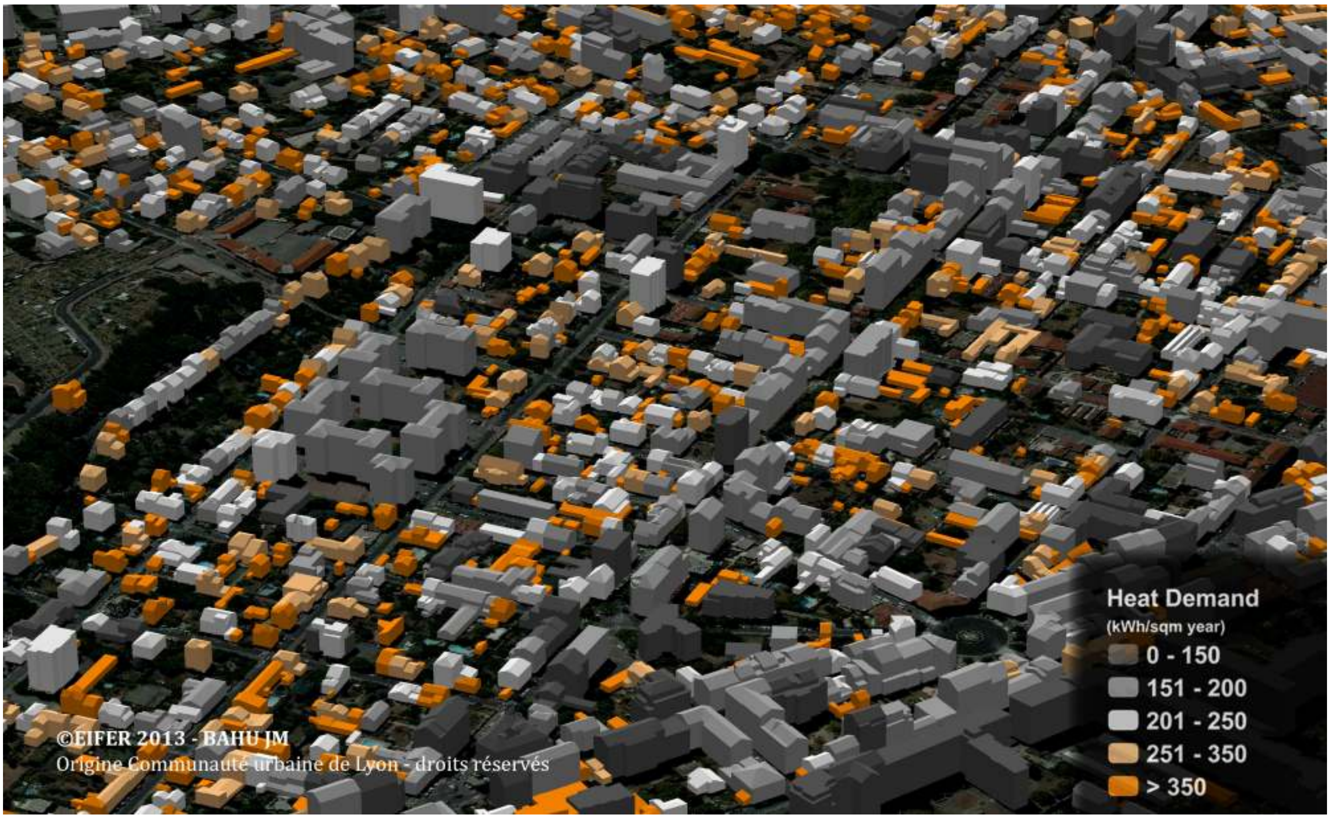

Figure 4. Results of the estimation of the heat demand of buildings. (Image courtesy of Jean-Marie Bahu, EIFER [126]).

For instance, estimating the energy demand is important to assess the benefit of energy-efficient retrofitting. Previtali *et al.* [135] note the use of 3D city models to assess the cost of retrofitting of a building. In combination with other data, 3D city models may be used for thermal assessment, and to determine thermal bridges and heat losses from the building envelope. In a related retrofit planning analysis, Tabrizi and Sanguinetti [136] have used the information of materials, weather data, and renewable energy sources.

4.1.3. Aiding Positioning

Löwner *et al.* [137] and Cappelle *et al.* [138] present methods using 3D city models to improve positioning in urban environments. The rationale is that it is possible to derive a position from photographs if it is possible to match the same perspective from a 3D city model, which is useful for urban canyons where satellite positioning may be less reliable. Coors *et al.* [139] have developed a related method aimed at tourism.

4.1.4. Determination of the Floorspace

3D city models may be used for estimating the internal size of a building in the legal framework (*i.e.*, net area, floorspace) [90,140,141]. For instance, according to the Dutch legislation the area where the ceiling is lower than 1.5 m is not taken into the area calculations. The floorspace can be inferred from the exterior of a building, without indoor data. This use case has a potential for taxation and valuation of buildings.

4.1.5. Classifying Building Types

Henn *et al.* [142] presented a method to detect the type of a building from its 3D geometry (e.g., apartment buildings and detached houses). The knowledge of the building type has an application in various domains. For instance, the distribution and share of a building type in a neighbourhood is of interest to marketing and real estate management.

4.2. Visualisation-Based Use Cases

4.2.1. Geo-Visualisation and Visualisation Enhancement

Visualisation is one of the fundamental purposes of 3D city models: it permits shape cognition and evaluation of complex spatial circumstances [143]. It is suggested that 3D city models generally provides an enhancement over 2D (map) data [144]. This use case is general and open-ended, since most of documented uses consist of visualising 3D data, for instance, for real estate [145], panoramic views [146], web visualisation [147–151], profiling [152], crime mapping [153,154], serious gaming [155,156], and augmented reality [157–167]. It is not our intention to further delineate each of these, as it entails more ambiguity with respect to the taxonomy. Therefore, only an overview of some applications is given.

3D city models are frequently used to enhance the presentation of results of analyses which are not necessarily related to GIS and 3D city models [168], for instance, economic activities [31], tsunami analysis [169,170], and planned wind farms [171]. Such visualisations are meant to aid scientists analysing large amounts of data. Other analyses where researchers and practitioners have used 3D visualisation include human activity [172], wind fields [173], and air quality data [173–175]. 3D city models are also used in traffic and flight simulators [176], and for background and fly-throughs in movies, documentaries, and news programs. Data used for these purposes are frequently procedurally generated [23,24,177].

4.2.2. Visibility Analysis

3D city models are indispensable for many visibility analyses, such as determining the line of sight (LoS) between two points in an urban environment and for estimating the volume of sight [178–181]. For instance, they are used in estimating the visibility of a landmark [182,183], assessing façade visibility for city marketing [184,185], in determining the optimal location for surveillance cameras [186–188], sensor coverage assessment [189], improving road safety [190], assessing sniper hazards [191], and in real estate mass valuation in the urban areas, based on the assumption that the view from an apartment is one of the factors driving its price [192–194]. Further applications involve predicting the visibility of GNSS satellites in the built environment and mitigating the multipath effect [195–204]. Such methods are valuable for enhancing map matching for navigation in urban canyons [205].

Visibility analyses with 3D city models are also used in studies on human perception of space [206,207], and more advanced analysis resulting in distinguishing the view of water bodies, green spaces, factories, and roads [208,209]. The information on the visibility from an apartment can also be used for taxation purposes [210].

Finally, 3D city models may be used for the estimation of the sky view factor (SVF)—the degree to which the sky is obscured by surrounding buildings [211]. Several researchers have demonstrated the use of 3D city models to estimate the SVF in their study areas for various purposes [212–219], e.g., for urban climate studies, and thermal comfort analyses.

4.2.3. Estimation of Shadows Cast by Urban Features

Estimating shadows cast by buildings is frequently used in urban planning [78], for instance, for assessing the impact of a planned building onto its surrounding. Such analyses are also legally required by some municipalities [87], such as The Hague in The Netherlands [220] and Mississauga in Canada [221]. Figure 5 illustrates a visualisation of a shadow analysis.

Figure 5. Estimating the shadow cast by a building for a few positions of the sun. For instance, this use case is valuable in assessing the effect that a proposed building design has on its surrounding. (Image courtesy of CyberCity 3D).

This use case is also essential in the estimation of the solar potential of buildings, which may negatively affect the photovoltaic yield of a solar panel [102,112,222–227]. In this context, this use case is closely related to the previously mentioned one of estimating the insolation of buildings, and they are often used together.

Further applications include estimating the thermal comfort of buildings [215,228], and the determination of solar envelopes [229,230]. In the energy domain, Lange and Hehl-Lange [231] study shadow casting from a proposed wind turbine towards the existing surrounding residential buildings.

Finally, this use case has also an application in agriculture, for instance, to estimate the predominantly shaded area of soil for calculating reduced growth for agricultural areas [62].

4.2.4. Estimation of the Propagation of Noise in an Urban Environment

3D data is used to create models that answer how urban citizens are harmed by noise pollution [76,232–234], and how to mitigate it, *i.e.*, where to place noise barriers [235,236]. In Europe, the utilisation of 3D city models for this application surged after the implementation of the Environmental noise Directive 2002/49/EC [237] which requires EU countries to produce strategic noise maps in order to inform the public about noise exposure and its effects [238,239]. While 2D GIS is frequently used for this purpose [76], 3D geoinformation provides an advantage over it, as due to refraction, sound levels may considerably variate at different elevations of the same planar coordinates [240].

Stoter *et al.* [77] produced a 3D noise map using 3D city models for obstacles in the noise propagation, and Law *et al.* [241] for the visual impression of the results of the simulation. In this use case the semantics are not required, but may be helpful. For instance, the knowledge of the type of the object may improve the results of the simulation of the propagation of the noise (e.g., noise barriers [242]), but also attributes such as material of the wall [243] (Figure 6).

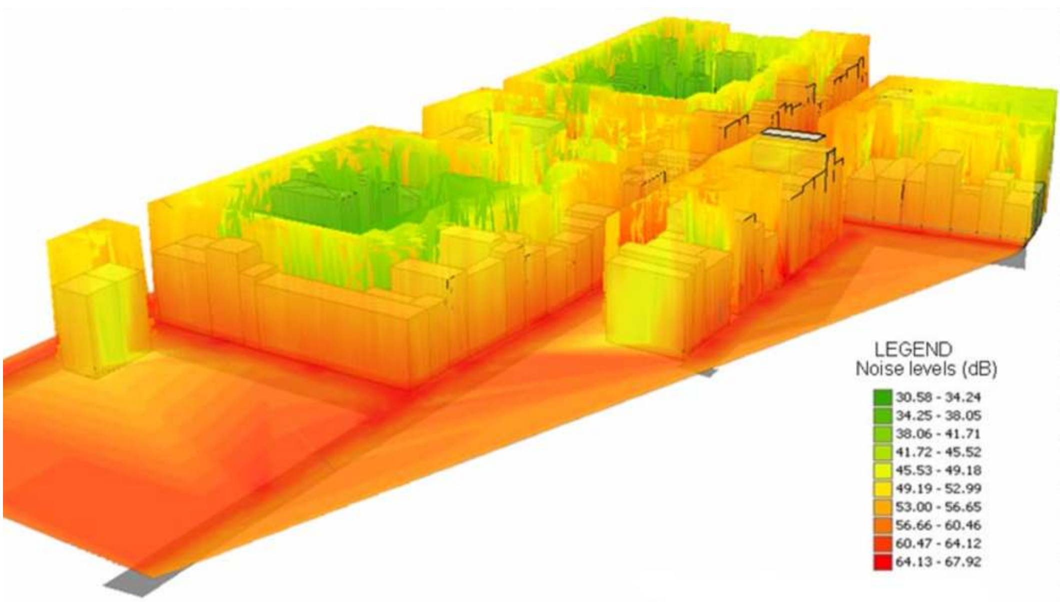

Figure 6. A 3D noise simulation derived with a 3D city model. (Image courtesy of Kurakula [243]).

4.2.5. 3D Cadastre

Some governments have recently been focusing on developing property registration in 3D to provide insights into complex property situations (Figure 7), such as vertical ownerships in buildings and subsurface constructions (e.g., cables and pipelines, parking garage). 3D city models have been used to store and manage data about the physical counterparts of the legal objects and similar techniques have been used to collect, store and disseminate data about 3D legal objects as for 3D city models [244–253].

In the visualisation context, Shojaei *et al.* [254] and Pouliot *et al.* [255] investigate portrayal aspects in 3D cadastre.

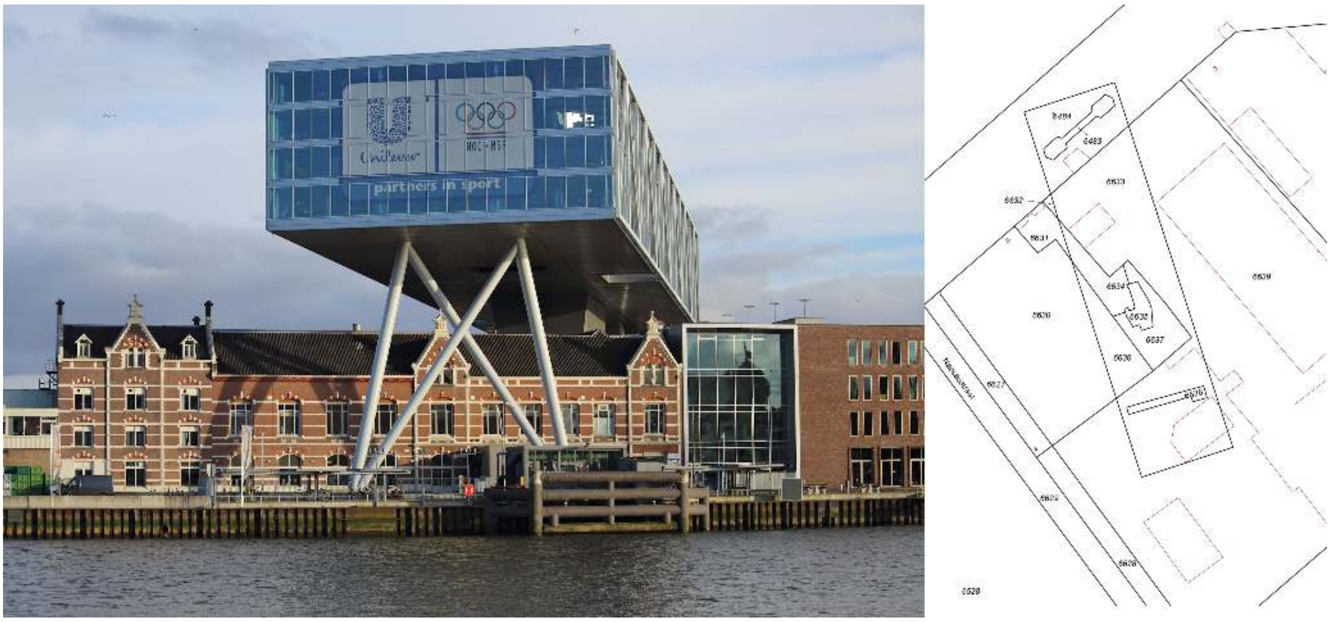

Figure 7. Example of a complex property situation (in Rotterdam, The Netherlands) in which the limitations of 2D cadastre are exposed. The corresponding cadastral map (courtesy of the Dutch Kadaster) shows that multiple small parcels are necessary to register a single object.

4.2.6. Visualisation for Navigation

3D city models, or sometimes 3D objects such as buildings on otherwise 2D visualisations, are used for facilitating the user's orientation in space for navigation purposes. Navigating urban spaces using 3D city models can help with orientation as it offers familiar landmarks; and it has often been proclaimed that their "more intuitive" nature than 2D maps provides more natural and realistic navigation cues [256–261]. At this point it is important to note that 2D aerial views (top views) are very important in navigation tasks as they provide overview information without occlusion as opposed to 3D views; and as mentioned earlier, they have a more consistent scale, thus are better for distance estimation tasks. In a choice experiment, it has been recently demonstrated that people use 3D visualisations roughly 30% of the time for navigation tasks [262]. The more realistic representations appear to be helpful for rapid shape cognition, thus possibly a mix of 2D and 3D views (multiple-linked views) are helpful in this case [263].

3D city models with semantic information provide added value in this use case as the visualisation can be enhanced to improve its function [264,265]. For instance, a landmark offers more navigational cues than a block of grey residential buildings, hence such can be emphasised in the visualisation.

4.2.7. Urban Planning

3D geoinformation is ubiquitous in urban planning for various tasks, especially the visualisation of the urban environment [53,266–274]. Urban planning is a use case with blurry boundaries and a large number of actors [275]. However, there have been many documented specific purposes, for instance, 3D geoinformation employed to facilitate park design [276], investigation of urban objects which would interfere with the planning of a new metro line [277], temporal analysis of changes in the landscape [278], for analysing the urban skyline [279,280], and for traffic simulation [281].

4.2.8. Visualisation for Communication of Urban Information to Citizenry

A visualisation application of 3D city models is to present the existing city and to disseminate urban information to citizens [40,282–284], and proposed developments and enhancements in a 3D virtual environment [285,286]. For instance, the model of the City of Adelaide in Australia provides a public consultation tool to assist in visualising transport, urban design and planning [287].

Because most members of the general public are not urban planning professionals, visualisation should be carefully designed [282], and here it is noted as a distinct use case.

3D models are used also to investigate local dynamics and best fitting urban indicators for development [288], and find their use also in tourism for virtual tours [289].

The application of communicating urban information to citizens, impact of proposed projects, and to present the development of a city often results in the materialisation of the 3D city models as physical models [283,290,291]. Further, within this use case, 3D city models may be used as a form of communication of cultural heritage [292].

4.2.9. Reconstruction of Sunlight Direction

Liu *et al.* [293] use 3D city models to determine the direction of the sunlight in photographs, which is useful for applications such as augmented reality, image processing, and object recognition.

4.2.10. Understanding Synthetic Aperture Radar Images

Several researchers in remote sensing have taken advantage of 3D city models to interpret high-resolution synthetic aperture radar (SAR) images and to predict the reflectivity of future SAR image acquisitions with a ray tracing analysis [294–298]. The methods involve simulating the acquisition with virtual sensors and analysing SAR scattering effects with buildings of different configurations.

4.2.11. Facility Management

Geoinformation is omnipresent in facility management. Recently, 3D models have been employed for this purpose, for instance, in managing ports [299], airports [300], and utility networks [301–303].

4.2.12. Automatic Scaffold Assembly

Løvset *et al.* [304] presented a specialised use of 3D models of buildings for automatically designing an optimal scaffold assembly for it. Their method also takes into account the terrain around the building, and it complies to governmental rules and safety regulations.

4.2.13. Emergency Response

3D geo-data can be used in disaster management and emergency response because they may provide valuable information such as the location of building entry points [305,306]. In this context, 3D city models can be used to determine the best position for the deployment of the ladder trucks before the arrival of firefighters at the scene [307].

4.2.14. Lighting Simulations

A seldom mentioned, but certainly distinct use case that we have encountered is the use of 3D city models in planning the lighting of landmarks [62]. Different lighting scenarios can be assessed without a physical implementation and visiting the sight, reducing associated costs.

4.2.15. Radio-Wave Propagation

Estimating the propagation of radio-waves for network planning is not a simple line of sight problem, since it involves concepts such as reflections and diffractions which are more advanced that a straight line analysis [308]. This is an early GIS use case where DEMs have been utilised to extract a terrain profile between a transmitter and receiver, and then to apply propagation models [309].

This use case later evolved to 3D city models, and applications date back as far as 1994 in a research by Yang *et al.* [310] who uses ray-tracing on 3D buildings. Subsequent estimations of the propagation of radio-waves in an urban environment regularly include 3D city models (e.g., [311–314]).

Lee [315] has shown how to use 3D city models to predict Wi-Fi coverage.

4.2.16. Computational Fluid Dynamics

Computational fluid dynamics (CFD) and related analyses frequently take advantage of 3D city models [316–319]. They have been used for a wide variety of applications related to microclimate analyses: for estimating the wind flow and evaluating the wind comfort [320,321], for understanding the urban thermal environment by estimating several environmental variables with CFD [322], estimating the physical effects of detonations and to determine the risks for structures and people [323] (Figure 8), predicting the ground surface temperature [324], investigating the influence of air conditioning heat rejection management systems of residential buildings [325], and for the prediction of air quality [326].

4.2.17. Estimating the Population in an Area

Some application domains may require the number of inhabitants in a specific area, for instance, assessing the population and number of affected buildings affected by the noise of a wind farm [62]. Since the size of a building and its type provide a cue on the number of residents, using 3D geoinformation to estimate the population has been a topic of several research papers [74,327–339].

The outcome of this use case can be used in multiple application domains. For instance, for optimising the coverage of mobile radio signal coverage (*i.e.*, to optimise the network to cover more people) [340], and emergency response for aid delivery and evacuation [341] (e.g., by estimating the affected population by a flooding [342]).

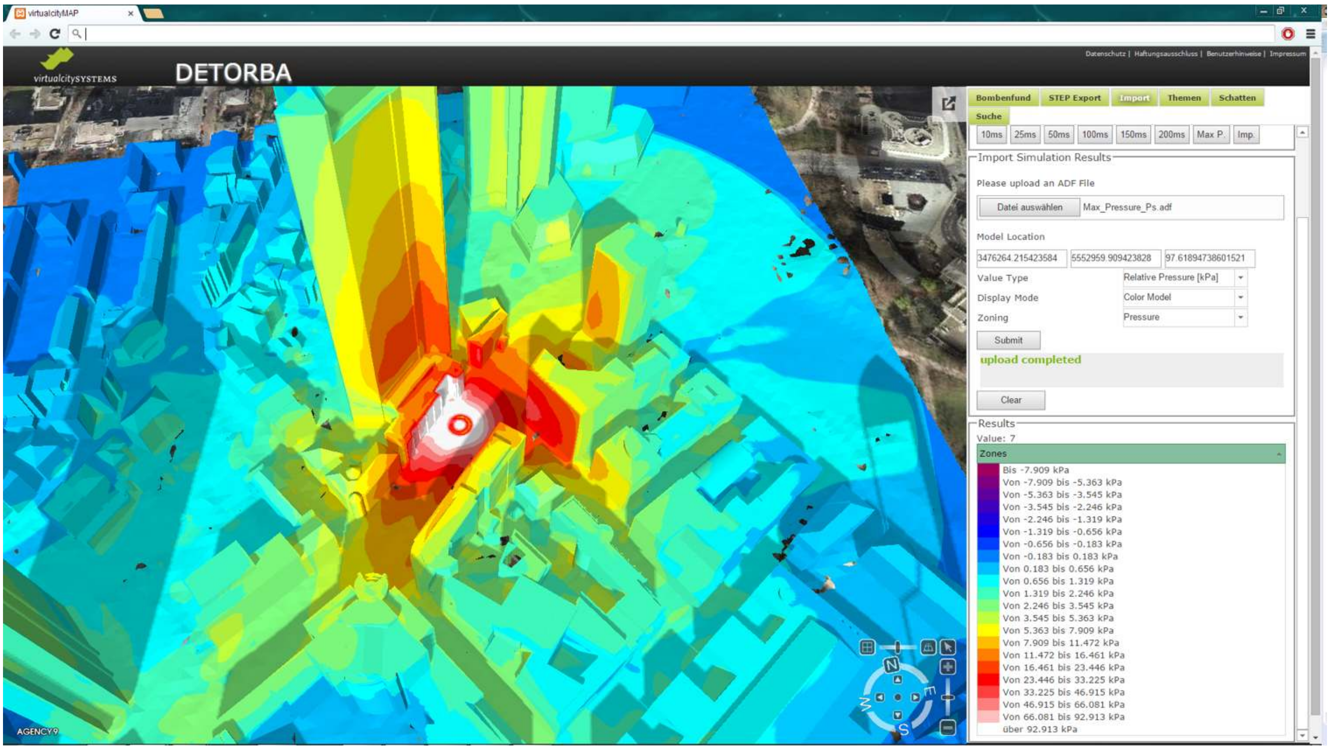

Figure 8. 3D city models may be used for simulation and analysis of the effects of explosions in urban areas. This example shows the blast pressure wave propagation in urban environments. Possible applications are the prediction of effects of structural integrity and soundness of the urban infrastructure, and aiding safety preparations for evacuation in the case of bomb discovery and defuse. (Image courtesy of virtualcitySYSTEMS).

4.2.18. Routing

Routing is a traditional 2D use case that is gaining more importance in 3D city models since they may be used for outdoor navigation [343]. Slingsby and Raper [344] investigate pedestrian navigation enhanced by data not available in 2D, such as ramps and steps. This use case is considered as separate from the use case of visualisation for navigation purposes, as here the focus is on deriving the optimal route, rather than route portrayal.

3D models containing indoor can be used for route finding and accessibility [345–352], with specific applications such as evacuation [307,353–357], navigating large train stations [358], determining indoor routes for the disabled [359], and locating the shortest path to the nearest automated external defibrillator [360]. Recent research efforts include the integration of indoor and outdoor routing for indoor emergency response facilitation [306].

4.2.19. Forecasting Seismic Damage

Christodoulou *et al.* [361] and Kemec *et al.* [362] use 3D city models to forecast and visualise damage to buildings from earthquakes, based on a framework for evaluating the seismic vulnerability. This use case is relevant for insurance, mitigation of earthquakes, and emergency response.

4.2.20. Flooding

Estimating the extent of floods has been a traditional topic in GIS, mostly with digital terrain models [363,364]. However, models of the propagation and impact of flooding by an overflow of water from water bodies or heavy precipitation can be improved by using 3D city models [365]. Varduhn *et al.* [366] and [367] use 3D models to assess the flood risk and the potential damage at a micro-scale. This use case is important for insurances (risk management), evacuation, and utility management.

4.2.21. Change Detection

Sharkawi and Abdul-Rahman [368], Pédrinis *et al.* [369], and Qin [370] use 3D city models for change detection for improving the quality of a city inventory. For instance, it is possible to detect if an extension to a home has been built [371].

4.2.22. Volumetric Density Studies

A volumetric study is a research of the built-environment density, the volume and intensity of activities it generates, and its influence over an urban space [36,372]. 3D city models are useful for volumetric analyses and they provide a substantial advantage over 2D data as they contain the height of buildings [36,373]. The information on the volumetric density may also be used for modelling the dispersion of urban pollutants [372,374,375].

4.2.23. Forest Management

Roßmann *et al.* [376] develop a forest management system that uses data of trees at a comparable level of detail as of building models. The system may be used for several purposes: forest navigation, developing a sustainable management strategy for harvesting, and predicting tree growth.

Remote sensing has been extensively employed for forestry, for instance, estimating the volume of timber [377], however, those applications are excluded from this analysis as they cannot be considered as 3D city models.

4.2.24. Archaeology

3D GIS is employed in archaeology, for instance, for urban reconstruction of ancient cities, modelling of archeological 3D objects and their attributes, managing excavations, testing reconstruction hypotheses, and analysing development of sites over time [378–388].

5. Conclusions

This paper provides a review of the current status of the application of 3D city models. We have shown that 3D city models are currently being used in dozens of application domains for diverse purposes, and we have categorised the uses of 3D city models into 29 use cases. The group of use cases relying on visualisation is larger than the other one, indicating that visualisation is an inseparable part of the workflows involving 3D city models.

We have encountered a number of issues in our survey, such as ambiguous terminology and fuzzy boundaries of use cases. These have prevented a straightforward inventory, and forced us to take many decisions that were often subjective. We believe that if other researchers attempted to carry out the same analysis with the same references, they might end up with a different grouping scheme and number of use cases. The lack of a clear definition for a 3D city model is partially responsible for such ambiguity. Nevertheless, we believe that we have captured virtually all uses of 3D city models, and that the decisions we have taken, while arbitrary, are justified and do not diminish the exposition of any of the applications.

Our analysis has revealed many interesting patterns. For instance, the development and utilisation of some use cases appear to be more popular in some countries than others, e.g., solar studies are encountered mostly in papers published by authors from Germany. Furthermore, it seems that there is no strong relation between the actual usage of a use case and the quantity of research papers describing it. As an example, navigation is arguably one of the most prominent use cases with a high usage share, but the topic of a few research papers.

A bibliometric analysis of the references that we carried out has exposed that the number of papers on applications has been steadily increasing (e.g., in the last year around 50 papers have been published, double the quantity published in 2010). Most of research papers documenting uses of 3D geoinformation have been published in the journal *Computers, Environment and Urban Systems* and the *3D GeoInfo* conference series. In the past few years new journals dedicated to GIS, e.g., this journal and the *International Journal of 3-D Information Modeling*, have been introduced, and have rapidly attracted a considerable number of papers dedicated to the utilisation of geoinformation. On the other hand, it is important to mention that applications of 3D city models have also been a topic of journals that do not squarely fit in the traditional definition of GIS, e.g., *Landscape and Urban Planning* and *Solar Energy*. Therefore, for following related developments, it is also important to take into account such non-GIS outlets.

We believe that this research is important for all stakeholders in the 3D city modelling community—they may use it to improve their product portfolios or understand the range of applications that 3D geoinformation can offer. It may also be a valuable input to research work that investigate the economic value of 3D geoinformation [46,389–391]. National mapping agencies (NMAs) may find it beneficial for defining use case scenarios and setting the proper requirements when procuring 3D datasets. Data producers may follow suit by designing their data product portfolios to match the requirements of a use case. Finally, researchers may find it useful as a reference that provides a more detailed insight into use cases, and our paper may serve a reference document for empirical studies related to 3D geovisualisation.

While the quantity of use cases we have cited already proves the valuable role and demand of 3D city models in the future, we expect new use cases and applications to further emerge through the following:

- Recent advances in augmented reality [392] and virtual reality [393]; developments in the fusion of computer graphics, GIS and BIM (e.g., [394–399]); and advances in procedural modelling [21,22,400–402] appear as promising *catalysts* that will contribute to providing 3D city models to practitioners.

- The majority of use cases rely on buildings, and not many use cases require models of other thematic classes, such as vegetation and bridges. We expect that, in the future, more use cases will take advantage of thematic features other than buildings.
- We expect that spatial analyses and use cases that are focused on 2D or 2.5D will evolve to take advantage of 3D city models when the case is appropriate (e.g., in logistics, for optimising delivery routes to customers [403]).
- Some application domains that have traditionally relied on 2D and/or 2.5D data are likely to embrace 3D use cases where third dimension is important. An example here is the house price models which can be augmented by already available 3D use cases such as estimating the environmental noise at a location.
- The use of 3D indoor models is increasing and we envisage more use cases with integrated indoor–outdoor models, such as existing cases of facility management and navigation [302,345]).

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Author Contributions

All authors have contributed to this paper with literature review and writing. FB conceived the idea and wrote most of the manuscript. Besides overall contributions, JS, HL, SZ, and AÇ have focused on content related to their area of expertise. AÇ has proposed the visualisation/non-visualisation categorisation of use cases. All authors have revised the manuscript.

Conflicts of Interest

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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