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

Filip Biljecki 1,*, Jantien Stoter 1, Hugo Ledoux 1, Sisi Zlatanova 1 and Arzu Çöltekin 2

1 3D geoinformation, Delft University of Technology, 2628 BL Delft, The Netherlands; E-Mails: j.e.stoter@tudelft.nl (J.S.); h.ledoux@tudelft.nl (H.L.); s.zlatanova@tudelft.nl (S.Z.)
2 Department of Geography, University of Zurich, 8057 Zurich, Switzerland; E-Mail: arzu@geo.uzh.ch

* Author to whom correspondence should be addressed; E-Mail: f.biljecki@tudelft.nl

Academic Editor: Wolfgang Kainz

Received: 2 November 2015 / Accepted: 8 December 2015 / Published: 18 December 2015

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
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](image-url) 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...
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.
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 m² [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 m² or the shaded volume in m³ [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 | Use Case |
|-----------------------------------|----------|
| Determining the suitability of a roof surface for installing photovoltaic panels | Estimation of the solar irradiation |
| Assessing the return of a building energy retrofit | Energy demand estimation |
| Map matching | Aiding positioning |
| Valuation of buildings | Determination of the floorspace |
| Semantic enrichment of data sets | Classifying building types |
| Flight simulation | Geo-visualisation and visualisation enhancement |
| Finding the optimal location to place a surveillance camera | Visibility analysis |
| Determination of solar envelopes | Estimation of shadows cast by urban features |
| Traffic planning | Estimation of the propagation of noise in an urban environment |
| Property registration | 3D cadastre |
| Navigation | Visualisation for navigation |
| Designing green areas | Urban planning |
| Virtual tours | Visualisation for communication of urban information to citizenry |
| Object recognition | Reconstruction of sunlight direction |
| Interpretation of radar data | Understanding SAR images |
| Managing utilities | Facility management |
| Civil engineering | Automatic scaffold assembly |
| Planning evacuation | Emergency response |
| Planning lighting of landmarks | Lighting simulations |
| Optimising radio infrastructure | Radio-wave propagation |
| Predicting air quality | Computational fluid dynamics |
| Crisis management | Estimating the population in an area |
| Understanding accessibility | Routing |
| Insurance | Forecasting seismic damage |
| Mitigating damage to utility management | Flooding |
| Urban inventory | Change detection |
| Urban studies | Volumetric density studies |
| Predicting tree growth | Forest management |
| Visualising ancient sites | Archaeology |
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].
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).](image)

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]).](image)

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 than 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 as 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]).

Acknowledgements

We are grateful to researchers, practitioners, and companies who have contributed to this paper with discussions and material, such as figures that have been used in the manuscript. This research is supported by (1) the Dutch Technology Foundation STW, which is part of The Netherlands Organisation for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs (project code: 11300); and (2) the Swiss National Science Foundation SNF (project ID: 200021_149670 /1).

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.
References

1. Billen, R.; Cutting-Decelle, A.F.; Marina, O.; de Almeida, J.P.; Matteo, C.; Falquet, G.; Leduc, T.; Métral, C.; Moreau, G.; Perret, J.; et al. 3D City Models and urban information: Current issues and perspectives. In 3D City Models and Urban Information: Current Issues and Perspectives—European COST Action TU0801; EDP Sciences: Les Ulis, France, 2014; pp. 1–118.

2. Zhu, Q.; Hu, M.; Zhang, Y.; Du, Z. Research and practice in three-dimensional city modeling. Geo-Spat. Inf. Sci. 2009, 12, 18–24.

3. Döllner, J.; Baumann, K.; Buchholz, H. Virtual 3D City Models as Foundation of Complex Urban Information Spaces. In Proceedings of the 11th International Conference on Urban Planning and Spatial Development in the Information Society, Vienna, Austria, 13–16 February 2006.

4. Lancelle, M.; Fellner, D.W. Current issues on 3D city models. In Proceedings of the Proceedings of the 25th International Conference in Image and Vision Computing, Queenstown, New Zealand, 8–9 November 2010; pp. 363–369.

5. Suveg, I.; Vosselman, G. Reconstruction of 3D building models from aerial images and maps. ISPRS J. Photogramm. Remote Sens. 2004, 58, 202–224.

6. Haala, N.; Kada, M. An update on automatic 3D building reconstruction. ISPRS J. Photogramm. Remote Sens. 2010, 65, 570–580.

7. Tomljenovic, I.; Höfle, B.; Tiede, D.; Blaschke, T. Building extraction from airborne laser scanning data: An analysis of the state of the art. Remote Sens. 2015, 7, 3826–3862.

8. Blaschke, T. Object based image analysis for remote sensing. ISPRS J. Photogramm. Remote Sens. 2010, 65, 2–16.

9. Ledoux, H.; Meijers, M. Topologically consistent 3D city models obtained by extrusion. Int. J. Geogr. Inf. Sci. 2011, 25, 557–574.

10. Arroyo Ohori, K.; Ledoux, H.; Stoter, J. A dimension-independent extrusion algorithm using generalised maps. Int. J. Geogr. Inf. Sci. 2015, 29, 1166–1186.

11. Shahzad, M.; Zhu, X.X. Robust reconstruction of building facades for large areas using spaceborne TomoSAR point clouds. IEEE Trans. Geosci. Remote Sens. 2015, 53, 752–769.

12. Zhu, X.X.; Shahzad, M. Facade reconstruction using multiview spaceborne TomoSAR point clouds. IEEE Trans. Geosci. Remote Sens. 2014, 52, 3541–3552.

13. Schmitt, M. Reconstruction of urban surface models from multi-aspect and multi-baseline interferometric SAR. Ph.D. Thesis, Technische Universität München, München, Germany, 2014.

14. Still, U.; Soergel, U.; Thoennessen, U. Potential and limits of InSAR data for building reconstruction in built-up areas. ISPRS J. Photogramm. Remote Sens. 2003, 58, 113–123.

15. Thiele, A.; Wegner, J.D.; Soergel, U. Building reconstruction from multi-aspect InSAR data. In Remote Sensing and Digital Image Processing; Soergel, U., Ed.; Springer: Dordrecht, The Netherlands, 2010; pp. 187–214.

16. Donkers, S.; Ledoux, H.; Zhao, J.; Stoter, J. Automatic conversion of IFC datasets to geometrically and semantically correct CityGML LOD3 buildings. Trans. GIS 2015, doi:10.1111/tgis.12162.
17. Yin, X.; Wonka, P.; Razdan, A. Generating 3D building models from architectural drawings: A survey. *IEEE Comput. Graph. Appl.* 2009, 29, 20–30.

18. Lewis, R.; Séquin, C. Generation of 3D building models from 2D architectural plans. *Comput. Aided Des.* 1998, 30, 765–779.

19. Sirmacek, B.; Lindenbergh, R. Accuracy assessment of building point clouds automatically generated from iphone images. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2014, XL-5, 547–552.

20. Rosser, J.; Morley, J.; Smith, G. Modelling of building interiors with mobile phone sensor data. *ISPRS Int. J. Geo-Inf.* 2015, 4, 989–1012.

21. Besuievsky, G.; Patow, G. Recent advances on LoD for procedural urban models. In Proceedings of the 2014 Workshop on Processing Large Geospatial Data, Cardiff, UK, 8 July 2014.

22. Tsiliakou, E.; Labropoulos, T.; Dimopoulou, E. Procedural modeling in 3D GIS environment. *Int. J. 3-D Inf. Model.* 2014, 3, 17–34.

23. Müller, P.; Wonka, P.; Haegler, S.; Ulmer, A.; van Gool, L. Procedural modeling of buildings. *ACM Trans. Graph.* 2006, 25, 614–623.

24. Smelik, R.M.; Tutenel, T.; Bidarra, R.; Benes, B. A Survey on procedural modelling for virtual worlds. *Comput. Graph. Forum* 2014, 33, 31–50.

25. Biljecki, F.; Ledoux, H.; Stoter, J. Error propagation in the computation of volumes in 3D city models with the Monte Carlo method. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* 2014, II-2, 31–39.

26. Martinović, A. Inverse Procedural Modeling of Buildings. Ph.D. Thesis, KU Leuven, Leuven, Belgium, 2015.

27. Over, M.; Schilling, A.; Neubauer, S.; Zipf, A. Generating web-based 3D City Models from OpenStreetMap: The current situation in Germany. *Comput. Environ. Urban Syst.* 2010, 34, 496–507.

28. Goetz, M. Towards generating highly detailed 3D CityGML models from OpenStreetMap. *Int. J. Geogr. Inf. Sci.* 2013, 27, 845–865.

29. Goetz, M.; Zipf, A. Towards defining a framework for the automatic derivation of 3D CityGML models from Volunteered Geographic Information. *Int. J. 3-D Inf. Model.* 2012, 1, 1–16.

30. Sinning-Meister, M.; Gruen, A.; Dan, H. 3D city models for CAAD-supported analysis and design of urban areas. *ISPRS J. Photogramm. Remote Sens.* 1996, 51, 196–208.

31. Shiode, N. 3D urban models: Recent developments in the digital modelling of urban environments in three-dimensions. *GeoJournal* 2001, 52, 263–269.

32. Coors, V.; Flick, S. Integrating levels of detail in a web-based 3D-GIS. In Proceedings of the 6th ACM International Symposium on Advances in Geographic Information Systems, Washington, DC, USA, 2–7 November 1998.

33. Stoter, J.; Zlatanova, S. 3D GIS, where are we standing? In Proceedings on the ISPRS Joint Workshop on Spatial, Temporal and Multi-Dimensional Data Modeling and Analysis, Cardiff, UK, 5–8 September 2003.

34. Ulm, K. Virtual 3D City Models—Satisfaction through sustainability. *Geomat. World* 2010, 18, 16–18.
35. Kolbe, T.H.; Gröger, G. Towards unified 3D city models. In Proceedings of the ISPRS Commission IV Joint Workshop—Challenges in Geospatial Analysis, Integration and Visualization II, Stuttgart, Germany, 8–9 September 2003.

36. Ahmed, F.C.; Sekar, S.P. Using three-dimensional volumetric analysis in everyday urban planning processes. Appl. Spat. Anal. Policy 2014, 8, 393–408.

37. Kolbe, T.H. Representing and exchanging 3D city models with CityGML. In 3D Geo-Information Sciences; Zlatanova, S., Lee, J., Eds.; Springer: Berlin, Germany, 2009; pp. 15–31.

38. Gröger, G.; Plümer, L. How to achieve consistency for 3D city models. GeoInformatica 2009, 15, 137–165.

39. Lemmens, M. Applying geo-information technology. In Geo-information. Technologies, Applications and the Environment; Springer Netherlands: Dordrecht, The Netherlands, 2011; pp. 229–258.

40. Batty, M.; Chapman, D.; Evans, S.; Haklay, M.; Kueppers, S.; Shiode, N.; Smith, A.; Torrens, P.M. Visualizing the City: Communicating Urban Design to Planners and Decision-Makers; Technical Report Paper 26; Centre for Advanced Spatial Analysis (UCL): London, UK, 2000.

41. Ross, L. Virtual 3D City Models in Urban Land Management—Technologies and Applications. Ph.D. Thesis, Technische Universität Berlin, Berlin, Germany, 2010.

42. Stoter, J.; Beetz, J.; Ledoux, H.; Reuvers, M.; Klooster, R.; Janssen, P.; Penninga, F.; Zlatanova, S.; van den Brink, L. Implementation of a national 3D standard: Case of The Netherlands. In Progress and New Trends in 3D Geoinformation Sciences; Springer: Berlin, Germany, 2012; pp. 277–298.

43. Stoter, J.; Vosselman, G.; Goos, J.; Zlatanova, S.; Verbree, E.; Klooster, R.; Reuvers, M. Towards a national 3D spatial data infrastructure: Case of The Netherlands. Photogramm.—Fernerkund.—Geoinf. 2011, 2011, 405–420.

44. Goos, J.; Klooster, R.; Stoter, J.; Verbree, E.; Vestjens, G.; Vosselman, G. 3D Pilot: Eindrapport Werkgroep Aanbod van 3D Geo-Informatie; Netherlands Geodetic Commission: Delft, The Netherlands, 2011.

45. Berntssen, M.; Danes, M.; Goos, J.; Klooster, R.; Kooijman, J.; Noordegraaf, L.; Stoter, J.; Veldhuis, C.; Vosselman, G. 3D Pilot: Eindrapport Werkgroep 3D Use Cases; Netherlands Geodetic Commission: Delft, The Netherlands, 2012.

46. Wong, K.K.Y. Economic Value of 3D Geographic Information; EuroSDR and the Department of Computer Science, University College London: London, UK, 2015.

47. Stoter, J.; Roensdorf, C.; Home, R.; Capstick, D.; Streilein, A.; Kellenberger, T.; Bayers, E.; Kane, P.; Dorsch, J.; Woźniak, P.; et al. 3D modelling with national coverage: Bridging the gap between research and practice. In Advances in 3D Geo-Information Sciences; Springer International Publishing: New York, NY, USA, 2015; pp. 207–225.

48. Cetl, V.; Tomić, H.; Lisjak, J. Primjena 3D Modela u Upravljanju Gradom; Faculty of Geodesy, University of Zagreb: Zagreb, Croatia, 2013.

49. Snyder, G.I. The benefits of improved national elevation data. Photogramm. Eng. Remote Sens. 2013, 79, 105–110.
50. Dassot, M.; Constant, T.; Fournier, M. The use of terrestrial LiDAR technology in forest science: application fields, benefits and challenges. *Ann. For. Sci.* 2011, 68, 959–974.

51. Axelsson, P. Processing of laser scanner data—algorithms and applications. *ISPRS J. Photogramm. Remote Sens.* 1999, 54, 138–147.

52. Zhang, X.; Zhu, Q. Applications of 3D city models based spatial analysis to urban design. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2004, XXXV/B2, 325–329.

53. Chen, R. The development of 3D city model and its applications in urban planning. In Proceedings of the 19th International Conference on Geoinformatics, Shanghai, China, 26 June 2011; pp. 1–5.

54. Shepherd, I.D.H. Travails in the Third Dimension: A Critical Evaluation of Three-dimensional Geographical Visualization. In *Geographic Visualization: Concepts, Tools and Applications*; Dodge, M., McDerby, M., Turner, M., Eds.; John Wiley & Sons, Ltd.: Chichester, UK, 2008; pp. 199–210.

55. Dall’Acqua, L.; Coltekin, A.; Noetzli, J. A comparative user evaluation of six alternative permafrost visualizations for reading and interpreting temperature information. In Proceedings of the GeoViz Hamburg 2013 Interactive Maps that Help People Think, Hamburg, Germany, 6–8 March 2013.

56. Savage, D.M.; Wiebe, E.N.; Devine, H.A. Performance of 2D versus 3D topographic representations for different task types. *Proc. Hum. Factors Ergon. Soc. Ann. Meet.* 2004, 48, 1793–1797.

57. St John, M.; Cowen, M.B.; Smallman, H.S.; Oonk, H.M. The use of 2D and 3D displays for shape-understanding versus relative-position tasks. *Hum. Factors* 2001, 43, 79–98.

58. Smallman, H.S.; Cook, M.B.; Manes, D.I.; Cowen, M.B. Naïve realism in terrain appreciation. In Proceedings of the 51st Annual Meeting of the Human Factors and Ergonomics Society, Baltimore, ML, USA, 1–5 October 2007.

59. Hegarty, M.; Smallman, H.S.; Stull, A.T.; Canham, M.S. Naïve cartography: How intuitions about display configuration can hurt performance. *Cartograph.: Int. J. Geogr. Inf. Geovis.* 2009, 44, 171–186.

60. Biljecki, F. A scientometric analysis of selected GIScience journals. *Int. J. Geogr. Inf. Sci.* 2016, doi:10.1080/13658816.2015.1130831.

61. Sanborn. *3D Cities™*; Sanborn: Colorado Springs, CO, USA, 2014.

62. Coors, V.; Holweg, D.; Matthias, E.; Petzold, B. Broschüre “3D-Stadtmödelle”. Ingoforum: Darmstadt, Germany, 2013; p. 20.

63. Billen, R.; Cutting-Decelle, A.F.; Métral, C.; Falquet, G.; Zlatanova, S.; Marina, O. Challenges of semantic 3D city models. *Int. J. 3-D Inf. Model.* 2015, 4, 68–76.

64. Gröger, G.; Plümer, L. CityGML—Interoperable semantic 3D city models. *ISPRS J. Photogramm. Remote Sens.* 2012, 71, 12–33.

65. Open Geospatial Consortium. *OGC City Geography Markup Language (CityGML) Encoding Standard 2.0.0*; Open Geospatial Consortium, 2012.

66. SwissTopo. *swissBUILDINGS3D 1.0. Vereinfachte 3D-Gebäude der Schweiz*; Swiss Federal Office of Topography: Wabern, Switzerland, 2010.
67. Stoter, J.; Ledoux, H.; Reuvers, M.; van den Brink, L.; Klooster, R.; Janssen, P.; Beetz, J.; Penninga, F.; Vosselman, G. Establishing and implementing a national 3D standard in The Netherlands. *Photogramm.—Fernerkund.—Geoinf.* 2013, 2013, 381–392.

68. Gröger, G.; Plümer, L. The interoperable building model of the European Union. In *Geoinformation for Informed Decisions*; Abdul-Rahman, A., Boguslawski, P., Anton, F., Said, M.N., Omar, K.M., Eds.; Springer International Publishing: New York, NY, USA, 2013; pp. 1–17.

69. Ordnance Survey. *OS MasterMap Topography Layer—Building Height Attribute. Getting Started Guide*, 1st ed.; Ordnance Survey: Southampton, UK, 2014.

70. AdV (Arbeitsgemeinschaft der Vermessungsverwaltungen). *Modellierungsbeispiele für 3D-Gebäudemodelle*; AdV: Berlin, Germany, 2013.

71. Aringer, K.; Roschlaub, R. Bavarian 3D building model and update concept based on LiDAR, image matching and cadastre information. In *Innovations in 3D Geo-Information Sciences*; Springer International Publishing: Cham, Switzerland, 2014; pp. 143–157.

72. Jacobson, I. *Object-Oriented Software Engineering: A Use Case Driven Approach*; Addison-Wesley: Reading, MA, USA, 1992.

73. Kaden, R.; Kolbe, T.H. Simulation-based total energy demand estimation of buildings using semantic 3D city models. *Int. J. 3-D Inf. Model.* 2014, 3, 35–53.

74. Lu, Z.; Im, J.; Quackenbush, L. A volumetric approach to population estimation using lidar remote sensing. *Photogramm. Eng. Remote Sens.* 2011, 77, 1145–1156.

75. Tavares, G.; Zsigraiova, Z.; Semiao, V.; Carvalho, M.G. Optimisation of MSW collection routes for minimum fuel consumption using 3D GIS modelling. *Waste Manag.* 2009, 29, 1176–1185.

76. de Kluijver, H.; Stoter, J. Noise mapping and GIS: Optimising quality and efficiency of noise effect studies. *Comput. Environ. Urban Syst.* 2003, 27, 85–102.

77. Stoter, J.; de Kluijver, H.; Kurakula, V. 3D noise mapping in urban areas. *Int. J. Geogr. Inf. Sci.* 2008, 22, 907–924.

78. Herbert, G.; Chen, X. A comparison of usefulness of 2D and 3D representations of urban planning. *Cartogr. Geogr. Inf. Sci.* 2015, 42, 22–32.

79. Taylor, S.M.; Breston, B.E.; Hall, F.L. The effect of road traffic noise on house prices. *J. Sound Vib.* 1982, 80, 523–541.

80. Cohen, J.P.; Coughlin, C.C. Spatial hedonic models of airport noise, proximity, and housing prices. *J. Reg. Sci.* 2008, 48, 859–878.

81. Wilhelmsson, M. The impact of traffic noise on the values of single-family houses. *J. Environ. Plan. Manag.* 2000, 43, 799–815.

82. Biljecki, F.; Ledoux, H.; Stoter, J.; Zhao, J. Formalisation of the level of detail in 3D city modelling. *Comput. Environ. Urban Syst.* 2014, 48, 1–15.

83. Coltekin, A.; Reichenbacher, T. High quality geographic services and bandwidth limitations. *Future Internet* 2011, 3, 379–396.

84. Biljecki, F.; Heuvelink, G.B.M.; Ledoux, H.; Stoter, J. Propagation of positional error in 3D GIS: estimation of the solar irradiation of building roofs. *Int. J. Geogr. Inf. Sci.* 2015, 29, 2269–2294.
85. Arroyo Ohori, K.; Ledoux, H.; Biljecki, F.; Stoter, J. Modeling a 3D city model and its levels of detail as a true 4D model. *ISPRS Int. J. Geo-Inf.* 2015, 4, 1055–1075.

86. Strzalka, A.; Monien, D.; Koukofikis, A.; Eicker, U. Sensitivity analysis for minimization of input data for urban scale heat demand forecasting. In Proceedings of the 14th International Conference on Sustainable Energy Technologies SET, Nottingham, UK, 25–27 August 2015; pp. 1–10.

87. Biljecki, F.; Ledoux, H.; Stoter, J. Does a finer level of detail of a 3D city model bring an improvement for estimating shadows? In *Advances in 3D Geoinformation*; Springer International Publishing: Cham, Switzerland, 2016, in press.

88. Richter, D.; Richter, K.F.; Winter, S. The impact of classification approaches on the detection of hierarchies in place descriptions. In *Advances in 3D Geo-Information Sciences*; Vandenbroucke, D., Bucher, B., Croma, J., Eds.; Springer International Publishing: Cham, Switzerland, 2013; pp. 191–206.

89. Stadler, A.; Kolbe, T.H. Spatio-semantic coherence in the integration of 3D city models. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2007, XXXVI-2/C43, 8.

90. Boeters, R.; Arroyo Ohori, K.; Biljecki, F.; Zlatanova, S. Automatically enhancing CityGML LOD2 models with a corresponding indoor geometry. *Int. J. Geogr. Inf. Sci.* 2015, 29, 2248–2268.

91. Garnett, R.; Freeburn, J.T. Visual acceptance of library-generated CityGML LOD3 building models. *Cartograph.: Int. J. Geogr. Inf. Geovis.* 2014, 49, 218–224.

92. Kumar, L.; Skidmore, A.K.; Knowles, E. Modelling topographic variation in solar radiation in a GIS environment. *Int. J. Geogr. Inf. Sci.* 1997, 11, 475–497.

93. Fath, K.; Stengel, J.; Sprenger, W.; Wilson, H.R.; Schultmann, F.; Kuhn, T.E. A method for predicting the economic potential of (building-integrated) photovoltaics in urban areas based on hourly Radiance simulations. *Sol. Energy* 2015, 116, 357–370.

94. Redweik, P.; Catita, C.; Brito, M. Solar energy potential on roofs and facades in an urban landscape. *Sol. Energy* 2013, 97, 332–341.

95. Eicker, U.; Nouvel, R.; Duminil, E.; Coors, V. Assessing passive and active solar energy resources in cities using 3D city models. *Energy Proced.* 2014, 57, 896–905.

96. Šúri, M.; Hofierka, J. A new GIS-based solar radiation model and its application to photovoltaic assessments. *Trans. GIS* 2004, 8, 175–190.

97. Santos, T.; Gomes, N.; Freire, S.; Brito, M.C.; Santos, L.; Tenedório, J.A. Applications of solar mapping in the urban environment. *Appl. Geogr.* 2014, 51, 48–57.

98. Jakubiec, J.A.; Reinhart, C.F. A method for predicting city-wide electricity gains from photovoltaic panels based on LiDAR and GIS data combined with hourly Daysim simulations. *Sol. Energy* 2013, 93, 127–143.

99. Szabó, S.; Enyedi, P.; Horváth, M.; Kovács, Z.; Burai, P.; Csoknyai, T.; Szabó, G. Automated registration of potential locations for solar energy production with Light Detection And Ranging (LiDAR) and small format photogrammetry. *J. Clean. Prod.* 2016, 112, 3820–3829.

100. Wiginton, L.K.; Nguyen, H.T.; Pearce, J.M. Quantifying rooftop solar photovoltaic potential for regional renewable energy policy. *Comput. Environ. Urban Syst.* 2010, 34, 345–357.
101. Peronato, G.; Rey, E.; Andersen, M. Sampling of building surfaces towards an early assessment of BIPV potential in urban contexts. In Proceedings of the 31st International PLEA Conference, Bologna, Italy, 9–11 September 2015.

102. Strzalka, A.; Alam, N.; Duminil, E.; Coors, V.; Eicker, U. Large scale integration of photovoltaics in cities. Appl. Energy 2012, 93, 413–421.

103. Redweik, P.; Catita, C.; Brito, M.C. 3D local scale solar radiation model based on urban LiDAR data. In Proceedings of the ISPRS Workshop High-Resolution Earth Imaging for Geospatial Information, Hannover, Germany, 14–17 June 2011; pp. 1–5.

104. Li, Z.; Zhang, Z.; Davey, K. Estimating geographical PV potential using LiDAR data for buildings in downtown San Francisco. Trans. GIS 2015, 19, 930–963.

105. Lukač, N.; Žlaus, D.; Seme, S.; Žalik, B.; Štumberger, G. Rating of roofs’ surfaces regarding their solar potential and suitability for PV systems, based on LiDAR data. Appl. Energy 2013, 102, 803–812.

106. Catita, C.; Redweik, P.; Pereira, J.; Brito, M.C. Extending solar potential analysis in buildings to vertical facades. Comput. Geosci. 2014, 66, 1–12.

107. Liang, J.; Gong, J.; Li, W.; Ibrahim, A.N. A visualization-oriented 3D method for efficient computation of urban solar radiation based on 3D—2D surface mapping. Int. J. Geogr. Inf. Sci. 2014, 28, 780–798.

108. Hofierka, J.; Zlocha, M. A new 3-D solar radiation model for 3-D city models. Trans. GIS 2012, 16, 681–690.

109. Hofierka, J.; Kaňuk, J. Assessment of photovoltaic potential in urban areas using open-source solar radiation tools. Renew. Energy 2009, 34, 2206–2214.

110. Liang, J.; Gong, J.; Zhou, J.; Zhou, J.; Ibrahim, A.N.; Li, M.; Li, M. An open-source 3D solar radiation model integrated with a 3D Geographic Information System. Environ. Model. Softw. 2015, 64, 94–101.

111. Carneiro, C.; Golay, F. Solar radiation over the urban texture: LiDAR data and image processing techniques for environmental analysis at city scale. In 3D Geo-Information Sciences; Lee, J., Zlatanova, S., Eds.; Springer: Berlin, Germany, 2009; pp. 319–340.

112. Jochem, A.; Höfle, B.; Rutzinger, M.; Pfeifer, N. Automatic roof plane detection and analysis in airborne Lidar point clouds for solar potential assessment. Sensors 2009, 9, 5241–5262.

113. Gooding, J.; Crook, R.; Tomlin, A.S. Modelling of roof geometries from low-resolution LiDAR data for city-scale solar energy applications using a neighbouring buildings method. Appl. Energy 2015, 148, 93–104.

114. Yu, B.; Liu, H.; Wu, J.; Lin, W.M. Investigating impacts of urban morphology on spatio-temporal variations of solar radiation with airborne LIDAR data and a solar flux model: a case study of downtown Houston. Int. J. Remote Sens. 2009, 30, 4359–4385.

115. Freitas, S.; Catita, C.; Redweik, P.; Brito, M.C. Modelling solar potential in the urban environment: State-of-the-art review. Renew. Sustain. Energy Rev. 2015, 41, 915–931.

116. Chwieduk, D.A. Recommendation on modelling of solar energy incident on a building envelope. Renew. Energy 2009, 34, 736–741.
117. Nichol, J.; Wong, M.S. Modeling urban environmental quality in a tropical city. *Landscape Urban Plan.* 2005, 73, 49–58.

118. Vermeulen, T.; Knopf-Lenoir, C.; Villon, P.; Beckers, B. Urban layout optimization framework to maximize direct solar irradiation. *Comput. Environ. Urban Syst.* 2015, 51, 1–12.

119. Aarsen, R.; Janssen, M.; Ramkisoen, M.; Biljecki, F.; Quak, W.; Verbree, E. Installed base registration of decentralised solar panels with applications in crisis management. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2015, XL-3/W3, 219–223.

120. Helbich, M.; Jochem, A.; Mücke, W.; Höfle, B. Boosting the predictive accuracy of urban hedonic house price models through airborne laser scanning. *Comput. Environ. Urban Syst.* 2013, 39, 81–92.

121. Saran, S.; Wate, P.; Srivastav, S.K.; Krishna Murthy, Y.V.N. CityGML at semantic level for urban energy conservation strategies. *Ann. GIS* 2015, 21, 27–41.

122. Robinson, D.; Stone, A. A simplified radiosity algorithm for general urban radiation exchange. *Build. Serv. Eng. Res. Technol.* 2005, 26, 271–284.

123. Carrión, D.; Lorenz, A.; Kolbe, T.H. Estimation of the energetic rehabilitation state of buildings for the city of Berlin using a 3D city model represented in CityGML. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2010, XXXVIII-4/W15, 31–35.

124. Krüger, A.; Kolbe, T.H. Building analysis for urban energy planning using key indicators on virtual 3D city models—The energy atlas of Berlin. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2012, XXXIX-B2, 145–150.

125. Strzalka, A.; Bogdahn, J.; Coors, V.; Eicker, U. 3D City modeling for urban scale heating energy demand forecasting. *HVAC&R Res.* 2011, 17, 526–539.

126. Bahu, J.M.; Koch, A.; Kremers, E.; Murshed, S.M. Towards a 3D spatial urban energy modelling approach. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* 2013, II-2/W1, 33–41.

127. Nouvel, R.; Schulte, C.; Eicker, U.; Pietruschka, D.; Coors, V. CityGML-based 3D city model for energy diagnostics and urban energy policy support. In Proceedings of the BS2013: 13th Conference of International Building Performance Simulation Association, Le Bourget Du Lac, France, 25–30 August 2013; pp. 218–225.

128. Nouvel, R.; Zirak, M.; Dastageeri, H.; Coors, V.; Eicker, U. Urban energy analysis based on 3D city model for national scale applications. In Proceedings of the Fifth German-Austrian IBPSA Conference (BauSIM 2014), Aachen, Germany, 22–24 September 2014; pp. 83–90.

129. Kaden, R.; Kolbe, T.H. City-wide total energy demand estimation of buildings using semantic 3D city models and statistical data. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* 2013, II-2/W1, 163–171.

130. Perez, D.; Kämpf, J.H.; Scartezzini, J.L. Urban area energy flow microsimulation for planning support: A calibration and verification study. *Int. J. Adv. Syst. Meas.* 2013, 6, 260–271.

131. Bahu, J.M.; Koch, A.; Kremers, E.; Murshed, S.M. Towards a 3D Spatial Urban Energy Modelling Approach. *Int. J. 3-D Inf. Model.* 2015, 3, 1–16.

132. Nouvel, R.; Mastrucci, A.; Leopold, U.; Baume, O.; Coors, V.; Eicker, U. Combining GIS-based statistical and engineering urban heat consumption models: Towards a new framework for multi-scale policy support. *Energy Build.* 2015, 107, 204–212.
133. Agugiaro, G. Energy planning tools and CityGML-based 3D virtual city models: Experiences from Trento (Italy). Appl. Geomat. 2015, doi:10.1007/s12518-015-0163-2.

134. Robinson, D.; Campbell, N.; Gaiser, W.; Kabel, K.; Le-Mouel, A.; Morel, N.; Page, J.; Stankovic, S.; Stone, A. SUNtool—A new modelling paradigm for simulating and optimising urban sustainability. Sol. Energy 2007, 81, 1196–1211.

135. Previtali, M.; Barazzetti, L.; Brumana, R.; Cuca, B.; Oreni, D.; Roncoroni, F.; Scaioni, M. Automatic façade modelling using point cloud data for energy-efficient retrofitting. Appl. Geomat. 2014, 6, 95–113.

136. Tabrizi, A.; Sanguinetti, P. Case study: Evaluation of renewable energy strategies using building information modeling and energy simulation. Int. J. 3-D Inf. Model. 2014, 2, 25–37.

137. Löwner, M.O.; Sasse, A.; Hecker, P. Needs and potential of 3D city information and sensor fusion technologies for vehicle positioning in urban environments. In Advances in 3D Geo-Information Sciences; Springer: Berlin, Germany, 2010; pp. 143–156.

138. Cappelle, C.; El Najjar, M.E.; Charpillet, F.; Pomorski, D. Virtual 3D city model for navigation in urban areas. J. Intell. Robot. Syst. 2011, 66, 377–399.

139. Coors, V.; Huch, T.; Kretschmer, U. Matching buildings: pose estimation in an urban environment. In Proceedings of the IEEE and ACM International Symposium on Augmented Reality (ISAR 2000), Munich, Germany, 5–6 October 2000; pp. 89–92.

140. Shiravi, S.; Zhong, M.; Beykaei, S.A.; Hunt, J.D.; Abraham, J.E. An assessment of the utility of LiDAR data in extracting base-year floorspace and a comparison with the census-based approach. Environ. Plan. B: Plan. Des. 2015, doi:10.1068/b130144p.

141. Boeters, R. Automatic Enhancement of CityGML LoD2 Models with Interiors and its Usability for Net Internal Area Determination. Master’s Thesis, Delft University of Technology, Delft, The Netherlands, 2013.

142. Henn, A.; Römer, C.; Gröger, G.; Plümer, L. Automatic classification of building types in 3D city models. GeoInformatica 2012, 16, 281–306.

143. Königer, A.; Bartel, S. 3D-GIS for urban purposes. GeoInformatica 1998, 2, 79–103.

144. Ellul, C.; Altenbuchner, J. Investigating approaches to improving rendering performance of 3D city models on mobile devices. Geo-Spat. Inf. Sci. 2014, 17, 73–84.

145. Rau, J.Y.; Cheng, C.K. A cost-effective strategy for multi-scale photo-realistic building modeling and web-based 3-D GIS applications in real estate. Comput. Environ. Urban Syst. 2013, 38, 35–44.

146. Pasewaldt, S.; Semmo, A.; Trapp, M.; Döllner, J. Multi-perspective 3D panoramas. Int. J. Geogr. Inf. Sci. 2014, 28, 2030–2051.

147. Zhang, L.; Han, C.; Zhang, L.; Zhang, X.; Li, J. Web-based visualization of large 3D urban building models. Int. J. Digit. Earth 2014, 7, 53–67.

148. Evans, A.; Romeo, M.; Bahrehmand, A.; Agenjo, J.; Blat, J. 3D graphics on the web: A survey. Comput. Graph. 2014, 41, 43–61.

149. Jochem, R.; Goetz, M. Towards interactive 3D city models on the web. Int. J. 3-D Inf. Model. 2012, 1, 26–36.
150. Mao, B.; Ban, Y. Online visualization of 3D city model using CityGML and X3DOM. *Cartograph.: Int. J. Geogr. Inf. Geovis.* 2011, 46, 109–114.

151. Coors, V. 3D-GIS in networking environments. *Comput. Environ. Urban Syst.* 2003, 27, 345–357.

152. Zhu, Q.; Zhao, J.; Du, Z.; Zhang, Y.; Xu, W.; Xie, X.; Ding, Y.; Wang, F.; Wang, T. Towards semantic 3D City modeling and visual explorations. In *Advances in 3D Geo-Information Sciences. Lecture Notes in Geoinformation and Cartography*; Kolbe, T.H., König, G., Nagel, C., Eds.; Springer: Berlin, Germany, 2011; pp. 275–294.

153. Wolff, M.; Asche, H. Geospatial modelling of urban security: A novel approach with virtual 3D city models. In *Computational Science and Its Applications—ICCSA 2008*; Springer: Berlin, Germany, 2008; pp. 42–51.

154. Wolff, M.; Asche, H. Towards geovisual analysis of crime scenes—A 3D crime mapping approach. In *Advances in GIScience*; Springer: Berlin, Germany, 2009; pp. 429–448.

155. Besuievsky, G.; Patow, G. Procedural modeling historical buildings for serious games. *Virtual Archeol. Rev.* 2013, 4, 160–166.

156. Rüppel, U.; Schatz, K. Designing a BIM-based serious game for fire safety evacuation simulations. *Adv. Eng. Inf.* 2011, 25, 600–611.

157. Portalés, C.; Lerma, J.L.; Navarro, S. Augmented reality and photogrammetry: A synergy to visualize physical and virtual city environments. *ISPRS J. Photogramm. Remote Sens.* 2010, 65, 134–142.

158. Verbree, E.; van Maren, G.; Germs, R.; Jansen, F.; Kraak, M.J. Interaction in virtual world views-linking 3D GIS with VR. *Int. J. Geogr. Inf. Sci.* 1999, 13, 385–396.

159. Germs, R.; van Maren, G.; Verbree, E.; Jansen, F.W. A multi-view VR interface for 3D GIS. *Comput. Graph.* 1999, 23, 497–506.

160. van Maren, G. Key to virtual insight: A 3D GIS and virtual reality system. In *Planning Support Systems in Practice*; Springer: Berlin, Germany, 2003; pp. 193–204.

161. Takase, Y.; Sho, N.; Sone, A.; Shimiya, K. Automatic generation of 3D city models and related applications. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2003, XXXIV-5/W10, 5.

162. Zhou, Q.; Zhang, W. A preliminary review on three-dimensional city model. *Geo-Spat. Inf. Sci.* 2004, 7, 79–88.

163. Ghadirian, P.; Bishop, I.D. Integration of augmented reality and GIS: A new approach to realistic landscape visualisation. *Landsc. Urban Plan.* 2008, 86, 226–232.

164. Vlahakis, V.; Ioannidis, N.; Karigiannis, J.; Tсотрос, M.; Gounaris, M.; Stricker, D.; Gleue, T.; Daehne, P.; Almeida, L. Archeoguide: An augmented reality guide for archaeological sites. *IEEE Comput. Graph. Appl.* 2002, 22, 52–60.

165. Richards-Rissetto, H.; Remondino, F.; Agugiaro, G.; Robertsson, J.; von Schwerin, J.; Girardi, G. Kinect and 3D GIS in archaeology. In Proceedings of the 18th International Conference on Virtual Systems and Multimedia (VSMM), Milan, Italy, 2–5 September 2012; IEEE: Milan, Italy, 2012; pp. 331–337.
166. Zamyadi, A.; Pouliot, J.; Bédard, Y. A three step procedure to enrich augmented reality games with CityGML 3D semantic modeling. In Progress and New Trends in 3D Geoinformation Sciences; Springer: Berlin, Germany, 2013; pp. 261–275.

167. Moreno, A.; Segura, Á.; Zlatanova, S.; Posada, J.; García-Alonso, A. Benefit of the integration of semantic 3D models in a fire-fighting VR simulator. Appl. Geomat. 2012, 4, 143–153.

168. Glander, T.; Döllner, J. Abstract representations for interactive visualization of virtual 3D city models. Comput. Environ. Urban Syst. 2009, 33, 375–387.

169. Kemec, S.; Duzgun, S.; Zlatanova, S.; Dilmen, D.I.; Yalciner, A.C. Selecting 3D urban visualisation models for disaster management: Fethiye tsunami inundation case. In Proceedings of the 3rd International Conference on Cartography and GIS, Nessebar, Bulgaria, 15–20 June 2010.

170. Patel, V.M.; Dholakia, M.B.; Singh, A.P. Tsunami risk 3D visualizations of Okha Coast, Gujarat (India). Int. J. Eng. Sci. Innov. Technol. 2013, 2, 130–138.

171. Manyoky, M.; Wissen Hayek, U.; Heutschi, K.; Pieren, R.; Grêt-Regamey, A. Developing a GIS-based visual-acoustic 3D simulation for wind farm assessment. ISPRS Int. J. Geo-Inf. 2014, 3, 29–48.

172. Kwan, M.P. Interactive geovisualization of activity-travel patterns using three-dimensional geographical information systems: a methodological exploration with a large data set. Transp. Res. Part C—Emerg. Technol. 2000, 8, 185–203.

173. Congote, J.; Moreno, A.; Kabongo, L.; Pérez, J.L.; San José, R.; Ruiz, O. Web based hybrid volumetric visualisation of urban GIS data. In Usage, Usability, and Utility of 3D City Models—European COST Action TU0801; Leduc, T., Moreau, G., Billen, R., Eds.; EDP Sciences: Nantes, France, 2012; pp. 1–6.

174. San José, R.; Pérez, J.L.; González-Barras, R.M. 3D visualization of air quality data. In Proceedings of the 11th International Conference “Reliability and Statistics in Transportation and Communication” (RelStat’11), 19–22 October 2011; pp. 1–9.

175. San José, R.; Pérez, J.L.; González, R.M. Advances in 3D visualization of air quality data. In Usage, Usability, and Utility of 3D City Models— European COST Action TU0801; Leduc, T., Moreau, G., Billen, R., Eds.; EDP Sciences: Nantes, France, 2012; pp. 1–13.

176. Yan, J.K. Advances in computer-generated imagery for flight simulation. IEEE Comput. Graph. Appl. 1985, 5, 37–51.

177. Besuievsky, G.; Patow, G. Customizable LoD for procedural architecture. Comput. Graph. Forum 2013, 32, 26–34.

178. Yang, P.P.; Putra, S.Y.; Li, W. Viewsphere: a GIS-based 3D visibility analysis for urban design evaluation. Environ. Plan. B: Plan. Des. 2007, 34, 971.

179. Liu, L.; Zhang, L.; Ma, J.; Zhang, L.; Zhang, X.; Xiao, Z.; Yang, L. An improved line-of-sight method for visibility analysis in 3D complex landscapes. Sci. China Inf. Sci. 2010, 53, 2185–2194.

180. Lonergan, C.; Hedley, N. Unpacking isovists: A framework for 3D spatial visibility analysis. Cartogr. Geogr. Inf. Sci. 2015, 43, 87–102.
181. Peters, R.; Ledoux, H.; Biljecki, F. Visibility analysis in a point cloud based on the medial axis transform. In Proceedings of the Eurographics Workshop on Urban Data Modelling and Visualisation 2015, Delft, The Netherlands, 23 November 2015; pp. 7–12.

182. Bartie, P.; Reitsma, F.; Kingston, S.; Mills, S. Advancing visibility modelling algorithms for urban environments. Comput. Environ. Urban Syst. 2010, 34, 518–531.

183. Delikostidis, I.; Engel, J.; Retzos, B.; van Elzakker, C.P.J.M.; Kraak, M.J.; Döllner, J. Increasing the usability of pedestrian navigation interfaces by means of Landmark visibility analysis. J. Navig. 2013, 66, 523–537.

184. Albrecht, F.; Moser, J.; Hijazi, I. Assessing façade visibility in 3D city models for city marketing. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 2013, XL-2/W2, 1–5.

185. Rabban, I.E.; Abdullah, K.; Ali, M.E.; Cheema, M.A. Visibility color map for a fixed or moving target in spatial databases. In Advances in Spatial and Temporal Databases; Springer International Publishing: Berlin, Germany, 2015; pp. 197–215.

186. Ying, M.; Jingjue, J.; Fulin, B. 3D-City Model supporting for CCTV monitoring system. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 2002, XXXIV, 1–4.

187. Yaagoubi, R.; Yarmani, M.; Kamel, A.; Khemiri, W. HybVOR: A voronoi-based 3D GIS approach for camera surveillance network placement. ISPRS Int. J. Geo-Inf. 2015, 4, 754–782.

188. Jung Moon, S.; Cheol Jeon, M.; Dam Eo, Y.; Bin Im, S.; Wook Park, B. Campus CCTV allocation simulation for maximizing monitoring areas. Adv. Inf. Sci. Serv. Sci. 2013, 5, 1192–1198.

189. Afghantoloee, A.; Doodman, S.; Karimipour, F.; Mostafavi, M.A. Coverage estimation of geosensor in 3D vector environments. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 2014, XL-2/W3, 1–6.

190. Bassani, M.; Grasso, N.; Piras, M. 3D GIS based evaluation of the available sight distance to assess safety of urban roads. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 2015, XL-3/W3, 137–143.

191. VanHorn, J.E.; Mosurinjohn, N.A. Urban 3D GIS modeling of terrorism sniper hazards. Soc. Sci. Comput. Rev. 2010, 28, 482–496.

192. Yu, S.M.; Han, S.S.; Chai, C.H. Modeling the value of view in high-rise apartments: a 3D GIS approach. Environ. Plan. B: Plan. Des. 2007, 34, 139–153.

193. Hamilton, S.E.; Morgan, A. Integrating lidar, GIS and hedonic price modeling to measure amenity values in urban beach residential property markets. Comput. Environ. Urban Syst. 2010, 34, 133–141.

194. Tomić, H.; Roić, M.; Mastelić Ivić, S. Use of 3D cadastral data for real estate mass valuation in the urban areas. In Proceedings of the 3rd International Workshop on 3D Cadastres: Developments and Practices, Shenzhen, China, 25–26 October 2012; pp. 73–86.

195. Wang, L.; Groves, P.D.; Ziebart, M.K. GNSS shadow matching: Improving urban positioning accuracy using a 3D city model with optimized visibility scoring scheme. Navigation 2013, 60, 195–207.

196. Hsu, L.T.; Gu, Y.; Kamijo, S. 3D building model-based pedestrian positioning method using GPS/GLONASS/QZSS and its reliability calculation. GPS Solut. 2015, doi:10.1007/s10291-015-0451-7.
197. Bradbury, J.; Ziebart, M.; Cross, P.A.; Boulton, P.; Read, A. Code multipath modelling in the urban environment using large virtual reality city models: Determining the local environment. *J. Navig.* 2007, 60, 95–105.

198. Wang, L.; Groves, P.D.; Ziebart, M.K. Multi-constellation GNSS performance evaluation for urban canyons using large virtual reality city models. *J. Navig.* 2012, 65, 459–476.

199. Kumar, R.; Petovello, M.G. A novel GNSS positioning technique for improved accuracy in urban canyon scenarios using 3D city model. In Proceedings of the ION GNSS+ 2014, Tampa, FL, USA, 8–12 September 2014.

200. Gang-jun, L.; Kefei, Z.; Falin, W.; Liam, D.; Retscher, G. Characterisation of current and future GNSS performance in urban canyons using a high quality 3-D urban model of Melbourne, Australia. *J. Appl. Geod.* 2009, 3, 15–24.

201. Kleijer, F.; Odijk, D.; Verbree, E. Prediction of GNSS availability and accuracy in urban environments case study schiphol airport. In *Location Based Services and TeleCartography II*; Springer Berlin Heidelberg: Berlin, Germany, 2009; pp. 387–406.

202. Bétaille, D.; Peyret, F.; Ortiz, M.; Miquel, S.; Fontenay, L. A new modeling based on urban trenches to improve GNSS positioning quality of service in cities. *IEEE Intell. Transp. Syst. Mag.* 2013, 5, 59–70.

203. Groves, P.D.; Jiang, Z. Height aiding, C/N 0 weighting and consistency checking for GNSS NLOS and multipath mitigation in urban areas. *J. Navig.* 2013, 66, 653–669.

204. Wada, Y.; Hsu, L.-T.; Gu, Y.; Kamijo, S. Optimization of 3D building models by GPS measurements. *GPS Solut* 2015, doi:10.1007/s10291-015-0504-y.

205. Piñana-Díaz, C.; Toledo-Moreo, R.; Toledo-Moreo, F.; Skarmeta, A. A two-layers based approach of an enhanced-mapfor urban positioning support. *Sensors* 2012, 12, 14508–14524.

206. Fisher-Gewirtzman, D. 3D models as a platform for urban analysis and studies on human perception of space. In *Usage, Usability, and Utility of 3D City Models—European COST Action TU0801*; Leduc, T., Moreau, G., Billen, R., Eds.; EDP Sciences: Nantes, France, 2012; pp. 1–16.

207. Fisher-Gewirtzman, D.; Natapov, A. Different approaches of visibility analyses applied on hilly urban environment. *Surv. Rev.* 2014, 46, 366–382.

208. Yasumoto, S.; Jones, A.P.; Nakaya, T.; Yano, K. The use of a virtual city model for assessing equity in access to views. *Comput. Environ. Urban Syst.* 2011, 35, 464–473.

209. Yasumoto, S.; Jones, A.; Yano, K.; Nakaya, T. Virtual city models for assessing environmental equity of access to sunlight: a case study of Kyoto, Japan. *Int. J. Geogr. Inf. Sci.* 2012, 26, 1–13.

210. Wilson, E. 3D Vision: BC Assessment’s Cool New Tools. Available online: http://www.rew.ca/ (accessed on 15 December 2015).

211. Johnson, G.T.; Watson, I.D. The determination of view-factors in urban canyons. *J. Clim. Appl. Meteorol.* 1984, 23, 329–335.

212. Brasebin, M.; Perret, J.; Mustière, S.; Weber, C. Measuring the impact of 3D data geometric modeling on spatial analysis: Illustration with Skyview factor. In *Usage, Usability, and Utility of 3D City Models— European COST Action TU0801*; Leduc, T., Moreau, G., Billen, R., Eds.; EDP Sciences: Nantes, France, 2012; pp. (02001)1–16.
213. Chen, L.; Ng, E.; An, X.; Ren, C.; Lee, M.; Wang, U.; He, Z. Sky view factor analysis of street canyons and its implications for daytime intra-urban air temperature differentials in high-rise, high-density urban areas of Hong Kong: a GIS-based simulation approach. *Int. J. Climatol.* **2012**, *32*, 121–136.

214. Gál, T.; Lindberg, F.; Unger, J. Computing continuous sky view factors using 3D urban raster and vector databases: comparison and application to urban climate. *Theor. Appl. Climatol.* **2009**, *95*, 111–123.

215. Hwang, R.L.; Lin, T.P.; Matzarakis, A. Seasonal effects of urban street shading on long-term outdoor thermal comfort. *Build. Environ.* **2011**, *46*, 863–870.

216. Besuievsky, G.; Barroso, S.; Beckers, B.; Patow, G. A configurable LoD for procedural urban models intended for daylight simulation. In *Proceedings of the Eurographics Workshop on Urban Data Modelling and Visualisation 2014*, Strasbourg, France, 6 April 2014; pp. 19–24.

217. Unger, J. Connection between urban heat island and sky view factor approximated by a software tool on a 3D urban database. *Int. J. Environ. Pollut.* **2009**, *36*, 59.

218. Hämmerle, M.; Gál, T.; Unger, J.; Matzarakis, A. Comparison of models calculating the sky view factor used for urban climate investigations. *Theor. Appl. Climatol.* **2011**, *105*, 521–527.

219. Muñoz, D.; Beckers, B.; Besuievsky, G.; Patow, G. Far-LoD: Level of detail for massive sky view factor calculations in large cities. In *Proceedings of the Eurographics Workshop on Urban Data Modelling and Visualisation 2015*, Delft, The Netherlands, 23 November 2015; pp. 1–6.

220. Den Haag. Voorstel van Het College Inzake Beleid Dakopbouwen (RIS 180461). Available online: [http://www.denhaag.nl/home.htm](http://www.denhaag.nl/home.htm) (accessed on 15 December 2015).

221. City of Mississauga. Standards for Shadow Studies. Available online: [www6.mississauga.ca](http://www6.mississauga.ca) (accessed on 15 December 2015).

222. Alam, N.; Coors, V.; Zlatanova, S.; Oosterom, P.J.M. Shadow effect on photovoltaic potentiality analysis using 3D city models. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2012**, *XXXIX-B8*, 209–214.

223. Alam, N.; Coors, V.; Zlatanova, S. Detecting shadow for direct radiation using CityGML models for photovoltaic potentiality analysis. In *Urban and Regional Data Management*; Ellul, C., Zlatanova, S., Rumor, M., Laurini, R., Eds.; CRC Press: London, UK, 2013; pp. 191–196.

224. Mardaljevic, J.; Rylatt, M. Irradiation mapping of complex urban environments: an image-based approach. *Energy Build.* **2003**, *35*, 27–35.

225. Nguyen, H.T.; Pearce, J.M. Incorporating shading losses in solar photovoltaic potential assessment at the municipal scale. *Sol. Energy* **2012**, *86*, 1245–1260.

226. Tooke, T.R.; Coops, N.C.; Voogt, J.A.; Meitner, M.J. Tree structure influences on rooftop-received solar radiation. *Landsc. Urban Plan.* **2011**, *102*, 73–81.

227. Eicker, U.; Monien, D.; Duminil, E.; Nouvel, R. Energy performance assessment in urban planning competitions. *Appl. Energy* **2015**, *155*, 323–333.

228. Yeziorno, A.; Shaviv, E. Shading: A design tool for analyzing mutual shading between buildings. *Sol. Energy* **1994**, *52*, 27–37.

229. Morello, E.; Ratti, C. Sunscapes: “Solar envelopes” and the analysis of urban DEMs. *Comput. Environ. Urban Syst.* **2009**, *33*, 26–34.
230. Knowles, R.L. The solar envelope: its meaning for energy and buildings. *Energy Build.* **2003**, *35*, 15–25.

231. Lange, E.; Hehl-Lange, S. Combining a participatory planning approach with a virtual landscape model for the siting of wind turbines. *J. Environ. Plan. Manag.* **2005**, *48*, 833–852.

232. Kurakula, V.; Kuffer, M. 3D noise modeling for urban environmental planning and management. In Proceedings of the 13th International Conference on Urban Planning in Information and Knowledge Society, Schrenk, M., Popovich, V., Engelke, D., Elisei, P., Eds.; 2008; pp. 517–523.

233. Pamanikabud, P.; Tansatcha, M. Geoinformatic prediction of motorway noise on buildings in 3D GIS. *Transp. Res. Part D: Transp. Environ.* **2009**, *14*, 367–372.

234. Lu, L.; Becker, T.; Löwner, M.O. 3D complete traffic noise analysis based on CityGML. In *Advances in 3D Geoinformation*; Springer International Publishing: Cham, Switzerland, 2016.

235. Ranjbar, H.R.; Gharagozlou, A.R.; Nejad, A.R.V. 3D analysis and investigation of traffic noise impact from Hemmat Highway located in Tehran on buildings and surrounding areas. *J. Geogr. Inf. Syst.* **2012**, *4*, 322–334.

236. Law, C.W.; Lee, C.K.; Lui, A.S.w.; Yeung, M.K.l.; Lam, K.c. Advancement of three-dimensional noise mapping in Hong Kong. *Appl. Acoust.* **2011**, *72*, 534–543.

237. EC. Directive 2002/49/EC of the European Parliament and of the Council. *Off. J. Eur. Communities* **2002**, *189/12*, 12–25.

238. Butler, D. Noise management: Sound and vision. *Nature* **2004**, *427*, 480–481.

239. Czerwinski, A.; Kolbe, T.H.; Plümer, L.; Elke, S.M. Interoperability and accuracy requirements for EU environmental noise mapping. In Proceedings of the International Conference on GIS and Sustainable Development (InterCarto—InterGIS 12), Berlin, Germany, 28–30 August 2006.

240. Kubiak, J.; Ławniczak, R. The propagation of noise in a built-up area (on the example of a housing estate in Poznań). *J. Maps* **2015**, doi:10.1080/17445647.2014.1001801.

241. Law, C.W.; Lee, C.K.; Tai, M.K. Visualization of complex noise environment by virtual reality technologies. In Proceedings of the Symposium of the campaign “Science in the Public Service”, Hong Kong, China, 27 April 2006; p. 8.

242. Czerwinski, A.; Kolbe, T.H.; Plümer, L.; Elke, S.M. Spatial data infrastructure techniques for flexible noise mapping strategies. In Proceedings of the 20th International Conference on Environmental Informatics-Managing Environmental Knowledge, Graz, Austria, 6–8 September 2006; pp. 99–106.

243. Kurakula, V. A GIS-Based Approach for 3D Noise Modelling Using 3D City Models. Master’s Thesis, International Institute for Geo-information Science and Earth Observation, Enschede, The Netherlands, 2007.

244. Billen, R.; Zlatanova, S. 3D spatial relationships model: a useful concept for 3D cadastre? *Comput. Environ. Urban Syst.* **2003**, *27*, 411–425.

245. Stoter, J.E.; van Oosterom, P.J.M. Technological aspects of a full 3D cadastral registration. *Int. J. Geogr. Inf. Sci.* **2005**, *19*, 669–696.

246. Stoter, J.; Ploeger, H.; van Oosterom, P. 3D cadastre in The Netherlands: Developments and international applicability. *Comput. Environ. Urban Syst.* **2013**, *40*, 56–67.
247. van Oosterom, P. Research and development in 3D cadastres. *Comput. Environ. Urban Syst.* 2013, 40, 1–6.

248. Çağdaş, V. An application domain extension to CityGML for immovable property taxation: A Turkish case study. *Int. J. Appl. Earth Observ. Geoinf.* 2013, 21, 545–555.

249. Frédéricque, B.; Raymond, K.; van Prooijen, K. *3D GIS Applied to Cadastre*; Bentley Systems Incorporated: Exton, PA, USA, 2011.

250. Guo, R.; Li, L.; Ying, S.; Luo, P.; He, B.; Jiang, R. Developing a 3D cadastre for the administration of urban land use: A case study of Shenzhen, China. *Comput. Environ. Urban Syst.* 2013, 40, 46–55.

251. Pouliot, J.; Roy, T.; Fouquet-Asselin, G.; Desgroseilliers, J. 3D Cadastre in the Province of Quebec: A First Experiment for the Construction of a Volumetric Representation. In *Advances in 3D Geo-Information Sciences*; Springer: Berlin, Germany, 2011; pp. 149–162.

252. Soon, K.H. A conceptual framework of representing semantics for 3D Cadastre in Singapore. In Proceedings of the 3rd International Workshop on 3D Cadastres, Shenzhen, China, 25–26 October 2012; pp. 361–379.

253. Vandyshheva, N.; Sapelnikov, S.; van Oosterom, P.J.M.; de Vries, M.E.; Spiering, B.; Wouters, R.; Hoogeveen, A.; Penkov, V. *The 3D Cadastre Prototype and Pilot in the Russian Federation*. International Federation of Surveyors (FIG): Rome, Italy, 2012.

254. Pouliot, J.; Wang, C.; Hubert, F.; Fuchs, V. Empirical assessment of the suitability of visual variables to achieve notarial tasks established from 3D condominium models. In *Innovations in 3D Geo-Information Sciences*; Springer International Publishing: Cham, Switzerland, 2014; pp. 195–210.

255. Schulze, M.; Germanchis, T. The employment of 3D in cartography—An overview. In *Multimedia Cartography*; Springer: Berlin, Germany, 2007; pp. 217–228.

256. Oulasvirta, A.; Estlander, S.; Nurminen, A. Embodied interaction with a 3D versus 2D mobile map. *Pers. Ubiquitous Comput.* 2009, 13, 303–320.

257. Schilling, A.; Coors, V.; Laakso, K. Dynamic 3D maps for mobile tourism applications. In *Map-Based Mobile Services*; Springer-Verlag: Berlin, Germany, 2005; pp. 227–239.

258. Rakkolainen, I.; Vainio, T. A 3D City Info for mobile users. *Comput. Graph.* 2001, 25, 619–625.

259. Nurminen, A. Mobile 3D city maps. *IEEE Comput. Graph. Appl.* 2008, 28, 20–31.

260. Musliman, I.A.; Abdul-Rahman, A.; Coors, V. 3D navigation for 3D-GIS—Initial requirements. In *Innovations in 3D Geo Information Systems*; Springer: Berlin, Germany, 2006; pp. 259–268.

261. Coltekin, A.; Lokka, I.E.; Boer, A. The utilization of publicly available map types by non-experts—A choice experiment. In Proceedings of the 27th International Cartographic Conference (ICC2015), Rio de Janeiro, Brazil, 23–28 August 2015.

262. Bernasocchi, M.; Çöltekin, A.; Gruber, S. An open source geovisual analytics toolbox for multivariate spatio-temporal data for environmental change modeling. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* 2012, I-2, 123–128.
264. Nedkov, S. Knowledge-based optimisation of 3D city models for car navigation devices. Master’s Thesis, Delft University of Technology, Delft, The Netherlands, 2012.

265. Mao, B.; Ban, Y.; Harrie, L. Real-time visualization of 3D city models at street-level based on visual saliency. Sci. China Earth Sci. 2015, 58, 448–461.

266. Ranzinger, M.; Gleixner, G. GIS datasets for 3D urban planning. Comput. Environ. Urban Syst. 1997, 21, 159–173.

267. Lewis, J.L.; Casello, J.M.; Groulx, M. Effective environmental visualization for urban planning and design: interdisciplinary reflections on a rapidly evolving technology. J. Urban Technol. 2012, 19, 85–106.

268. Pullar, D.V.; Tidey, M.E. Coupling 3D visualisation to qualitative assessment of built environment designs. Landsc. Urban Plan. 2001, 55, 29–40.

269. Sabri, S.; Pettit, C.J.; Kalantari, M.; Rajabifard, A.; White, M.; Lade, O.; Ngo, T. What are essential requirements in planning for future cities using open data infrastructures and 3D data models? In Proceedings of the 14th International Conference on Computers in Urban Planning and Urban Management, Cambridge, MA, USA, 7–10 July 2015.

270. Métral, C.; Falquet, G.; Vonlanthen, M. An ontology-based model for urban planning communication. In Ontologies for Urban Development; Springer: Berlin, Germany, 2007; pp. 61–72.

271. Kibria, M.S.; Zlatanova, S.; Itard, L.; Dorst, M. GeoVEs as tools to communicate in urban projects: Requirements for functionality and visualization. In 3D Geo-Information Sciences; Springer: Berlin, Germany, 2009; pp. 379–395.

272. Appleton, K.; Lovett, A. GIS-based visualisation of rural landscapes: Defining ”sufficient” realism for environmental decision-making. Landsc. Urban Plan. 2003, 65, 117–131.

273. Benner, J.; Geiger, A.; Häfele, K.H. Concept for building licensing based on standardized 3d geo information. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 2010, XXXVIII-4/W15, 9–12.

274. Leszek, K. Environmental and urban spatial analysis based on a 3D city model. In Computational Science and Its Applications—ICCSA 2015; Springer International Publishing: New York, NY, USA, 2015; pp. 633–645.

275. Isikdag, U.; Zlatanova, S. Interactive modelling of buildings in Google Earth: A 3D tool for Urban Planning. In Developments in 3D Geo-Information Sciences; Springer: Berlin, Germany, 2010; pp. 52–70.

276. Lu, S.; Wang, F. Computer aided design system based on 3D GIS for park design. In Computer, Intelligent Computing and Education Technology; CRC Press: London, UK; 2014; pp. 413–416.

277. Moser, J.; Albrecht, F.; Kosar, B. Beyond visualisation—3D GIS analyses for virtual city models. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 2010, XXXVIII-4/W15, 143–146.

278. Kańuk, J.; Gallay, M.; Hofierka, J. Generating time series of virtual 3-D city models using a retrospective approach. Landsc. Urban Plan. 2015, 139, 40–53.

279. Guney, C.; Akdag Girginkaya, S.; Cagdas, G.; Yavuz, S. Tailoring a geomodel for analyzing an urban skyline. Landsc. Urban Plan. 2012, 105, 160–173.

280. Czyńska, K.; Rubinowicz, P. Application of 3D virtual city models in urban analyses of tall buildings—Today practice and future challenges. Architect. Artibus 2014, 19, 9–13.
281. Chun, W.; Ge, C.; Yanyan, L.; Horne, M. Virtual-reality based integrated traffic simulation for urban planning. In Proceedings of the 2008 International Conference on Computer Science and Software Engineering, Wuhan, China, 15 August 2008; pp. 1137–1140.

282. Wu, H.; He, Z.; Gong, J. A virtual globe-based 3D visualization and interactive framework for public participation in urban planning processes. *Comput. Environ. Urban Syst.* **2010**, *34*, 291–298.

283. Franić, S.; Bačić-Deprato, I.; Novaković, I. 3D model and a scale model of the City of Zagreb. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2009**, *XXXVIII-2/W11*, 1–7.

284. Döllner, J.; Kolbe, T.H.; Liecke, F.; Sgouros, T.; Teichmann, K. The virtual 3D city model of Berlin—Managing, integrating, and communicating complex urban information. In Proceedings of the 25th Urban Data Management Symposium (UDMS 2006), Aalborg, Denmark, 15–17 May 2006; pp. 1–12.

285. Buhur, S.; Ross, L.; Büyüksalih, G.; Baz, I. 3D city modelling for planning activities, case study: Haydarpasa train station, haydarpasa port and surrounding backside zones, Istanbul. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2009**, *XXXVIII-I-4-7/W5*, 1–6.

286. City of Perth. *Planning and Development Application. 3D Model Specification*; City of Perth: Perth, Australia, 2013.

287. Adelaide City Council. *Development Information Guide of the Adelaide 3D City Model: Frequently Asked Questions for Architects, Designers and Developers*; Adelaide City Council: Adelaide, Australia, 2009.

288. Marina, O.; Masala, E.; Pensa, S.; Stavric, M. Interactive model of urban development in residential areas in Skopje. In *Usage, Usability, and Utility of 3D City Models—European COST Action TU0801*; Leduc, T., Moreau, G., Billen, R., Eds.; EDP Sciences: Nantes, France, 2012; pp. (02004)1–12.

289. Koutsoudis, A.; Arnaoutoglou, F.; Chamzas, C. On 3D reconstruction of the old city of Xanthi. A minimum budget approach to virtual touring based on photogrammetry. *J. Cult. Herit.* **2007**, *8*, 26–31.

290. Novaković, I. 3D model of Zagreb. *GIM Int.* **2011**, *25*, 25–29.

291. Ghawana, T.; Zlatanova, S. 3D printing for urban planning: A physical enhancement of spatial perspective. In *Urban and Regional Data Management UDMS Annual 2013*; Urban and Regional Data Management: UDMS Annual 2013: London, UK, 2013; pp. 211–224.

292. Trapp, M.; Semmo, A.; Pokorski, R.; Herrmann, C.D.; Döllner, J.; Eichhorn, M.; Heinzelmann, M. Communication of digital cultural heritage in public spaces by the example of Roman Cologne. In *Digital Heritage*; Springer: Berlin, Germany, 2010; pp. 262–276.

293. Liu, Y.; Gevers, T.; Li, X. Estimation of sunlight direction using 3D object models. *IEEE Trans. Image Process.* **2015**, *24*, 932–942.

294. Auer, S.; Hinz, S.; Bamler, R. Ray-tracing simulation techniques for understanding high-resolution SAR images. *IEEE Trans. Geosci. Remote Sens.* **2010**, *48*, 1445–1456.

295. Franceschetti, G.; Iodice, A.; Riccio, D.; Ruello, G. SAR raw signal simulation for urban structures. *IEEE Trans. Geosci. Remote Sens.* **2003**, *41*, 1986–1995.
296. Margarit, G.; Mallorqui, J.J.; Pipia, L. Polarimetric characterization and temporal stability analysis of urban target scattering. *IEEE Trans. Geosci. Remote Sens.* **2010**, *48*, 2038–2048.

297. Franceschetti, G.; Iodice, A.; Riccio, D. A canonical problem in electromagnetic backscattering from buildings. *IEEE Trans. Geosci. Remote Sens.* **2002**, *40*, 1787–1801.

298. Margarit, G.; Mallorqui, J.J.; Lopez-Martinez, C. Grecosar, a SAR simulator for complex targets: Application to urban environments. In Proceedings of the 2007 IEEE International Geoscience and Remote Sensing Symposium, Barcelona, Spain, 23–27 July 2007; IEEE: Barcelona, Spain, 2007; pp. 4160–4163.

299. Zlatanova, S.; Beetz, J. 3D spatial information infrastructure: The case of Port Rotterdam. In *Usage, Usability, and Utility of 3D City Models—European COST Action TU0801*; Leduc, T., Moreau, G., Billen, R., Eds.; EDP Sciences: Nantes, France, 2012; pp. 1–8.

300. Tang, K.; Xu, J.K. Research on application of airport simulation system based on 3D GIS. *Appl. Mech. Mater.* **2012**, *198-199*, 717–720.

301. Liu, R.; Issa, R.R.A. 3D visualization of sub-surface Pipelines in connection with the building utilities: Integrating GIS and BIM for facility management. In Proceedings of the International Conference on Computing in Civil Engineering, Clearwater Beach, FL, USA, 17–20 June 2012; American Society of Civil Engineers: Clearwater Beach, FL, USA, 2012; pp. 341–348.

302. Hijazi, I.H.; Ehlers, M.; Zlatanova, S. NIBU: A new approach to representing and analysing interior utility networks within 3D geo-information systems. *Int. J. Digit. Earth* **2012**, *5*, 22–42.

303. Becker, T.; Nagel, C.; Kolbe, T.H. Semantic 3D modeling of multi-utility networks in cities for analysis and 3D visualization. In *Progress and New Trends in 3D Geoinformation Sciences*; Springer: Berlin, Germany, 2013; pp. 41–62.

304. Løvset, T.; Ulvang, D.M.; Bekkvik, T.C.; Villanger, K.; Viola, I. Rule-based method for automatic scaffold assembly from 3D building models. *Comput. Graph.* **2013**, *37*, 256–268.

305. Kwan, M.P.; Lee, J. Emergency response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments. *Comput. Environ. Urban Syst.* **2005**, *29*, 93–113.

306. Tashakkori, H.; Rajabifard, A.; Kalantari, M. A new 3D indoor/outdoor spatial model for indoor emergency response facilitation. *Build. Environ.* **2015**, *89*, 170–182.

307. Chen, L.C.; Wu, C.H.; Shen, T.S.; Chou, C.C. The application of geometric network models and building information models in geospatial environments for fire-fighting simulations. *Comput. Environ. Urban Syst.* **2014**, *45*, 1–12.

308. Corre, Y.; Lostanlen, Y. Three-dimensional urban EM wave propagation model for radio network planning and optimization over large areas. *IEEE Trans. Veh. Technol.* **2009**, *58*, 3112–3123.

309. Leibherz, M.; Wiesbeck, W.; Krank, W. A versatile wave propagation model for the VHF/UHF range considering three-dimensional terrain *IEEE Trans. Antennas Propag.* **1992**, *40*, 1121–1131.

310. Yang, G.; Pahlavan, K.; Lee, J.F.; Dagen, A.J.; Van Craeynest, J. Prediction of radio wave propagation in four blocks of New York City using 3D ray tracing. In Proceedings of the 5th IEEE International Symposium on Wireless Networks Catching the Mobile Future, Hague, The Netherlands, 18–23 September 1994.
311. Rautiainen, T.; Wolfle, G.; Hoppe, R. Verifying path loss and delay spread predictions of a 3D ray tracing propagation model in urban environment. In Proceedings of the IEEE 56th Vehicular Technology Conference, Vancouver, Canada, 24–28 September 2002.

312. Wagen, J.F.; Rizk, K. Radiowave propagation, building databases, and GIS: anything in common? A radio engineer’s viewpoint. *Environ. Plan. B Plan. Des.* **2003**, *30*, 767–787.

313. Yun, Z.; Iskander, M.F.; Lim, S.Y.; He, D.; Martinez, R. Radio wave propagation prediction based on 3-D building structures extracted from 2-D images. *Antennas Wirel. Propag. Lett.* **2007**, *6*, 557–559.

314. Beekhuizen, J.; Heuvelink, G.B.M.; Huss, A.; Bürgi, A.; Kromhout, H.; Vermeulen, R. Impact of input data uncertainty on environmental exposure assessment models: A case study for electromagnetic field modelling from mobile phone base stations. *Environ. Res.* **2014**, *135*, 148–155.

315. Lee, G. 3D coverage location modeling of Wi-Fi access point placement in indoor environment. *Comput. Environ. Urban Syst.* **2015**, *54*, 326–335.

316. Asawa, T.; Hoyano, A.; Yoshida, T.; Takata, M. A new approach to microclimate analysis using airborne remote sensing, 3D-GIS and CFD simulation. In Proceedings of the 1st Asia Conference of International Building Performance Simulation Association, Shanghai, China, 25–27 November 2012; pp. 1–8.

317. Ujang, U.; Anton, F.; Abdul-Rahman, A. Unified data model of urban air pollution dispersion and 3D spatial city model: Groundwork assessment towards sustainable urban development for Malaysia. *J. Environ. Prot.* **2013**, *4*, 701–712.

318. Musy, M.; Malys, L.; Morille, B.; Inard, C. The use of SOLENE-microclimat model to assess adaptation strategies at the district scale. *Urban Clim.* **2015**, *14*, 213–223.

319. Lee, D.; Pietrzyk, P.; Donkers, S.; Liem, V.; van Oostveen, J.; Montazeri, S.; Boeters, R.; Colin, J.; Kastendeuch, P.; Nerry, F.; *et al.* Modeling and observation of heat losses from buildings: The impact of geometric detail on 3D heat flux modeling. In Proceedings of the 33rd European Association of Remote Sensing Laboratories (EARSeL) Symposium, Matera, Italy, 3–6 June 2013; pp. 353–372.

320. Amorim, J.H.; Valente, J.; Pimentel, C.; Miranda, A.I.; Borrego, C. Detailed modelling of the wind comfort in a city avenue at the pedestrian level. In *Usage, Usability, and Utility of 3D City Models— European COST Action TU0801*; Leduc, T., Moreau, G., Billen, R., Eds.; EDP Sciences: Nantes, France, 2012; pp. (03008)1–6.

321. Janssen, W.D.; Blocken, B.; van Hooff, T. Pedestrian wind comfort around buildings: Comparison of wind comfort criteria based on whole-flow field data for a complex case study. *Build. Environ.* **2013**, *59*, 547–562.

322. Maragkogiannis, K.; Kolokotsa, D.; Maravelakis, E.; Konstantaras, A. Combining terrestrial laser scanning and computational fluid dynamics for the study of the urban thermal environment. *Sustain. Cities Soc.* **2014**, *13*, 207–216.

323. Willenborg, B. Simulation of explosions in urban space and result analysis based on CityGML-City Models and a cloud-based 3D-Webclient. Master’s Thesis, Technical University Munich, Munich, Germany, 2015.
324. Upadhyay, G.; Kämpf, J.; Scartezzini, J.L. Ground temperature modelling: The case study of Rue des Maraîchers in Geneva. In Proceedings of the Eurographics Workshop on Urban Data Modelling and Visualisation 2014, Strasbourg, France, 6 April 2014; pp. 13–18.

325. Hsieh, C.M.; Aramaki, T.; Hanaki, K. Managing heat rejected from air conditioning systems to save energy and improve the microclimates of residential buildings. Comput. Environ. Urban Syst. 2011, 35, 358–367.

326. Zheng, M.H.; Guo, Y.R.; Ai, X.Q.; Qin, T.; Wang, Q.; Xu, J.M. Coupling GIS with CFD modeling to simulate urban pollutant dispersion. In Proceedings of the 2010 International Conference on Mechanic Automation and Control Engineering (MACE), Wuhan, China, 25–27 June 2008.

327. Kunze, C.; Hecht, R. Semantic enrichment of building data with volunteered geographic information to improve mappings of dwelling units and population. Comput. Environ. Urban Syst. 2015, 53, 4–18.

328. Wu, S.S.; Qiu, X.; Wang, L. Population estimation methods in GIS and remote sensing: A review. GISci. Remote Sens. 2005, 42, 80–96.

329. Lwin, K.; Murayama, Y. A GIS approach to estimation of building population for micro-spatial analysis. Trans. GIS 2009, 13, 401–414.

330. Wu, S.S.; Wang, L.; Qiu, X. Incorporating GIS building data and census housing statistics for sub-block-level population estimation. Prof. Geogr. 2008, 60, 121–135.

331. Ural, S.; Hussain, E.; Shan, J. Building population mapping with aerial imagery and GIS data. Int. J. Appl. Earth Obs. Geoinf. 2011, 13, 841–852.

332. Silván-Cárdenas, J.L.; Wang, L.; Rogerson, P.; Wu, C.; Feng, T.; Kamphaus, B.D. Assessing fine-spatial-resolution remote sensing for small-area population estimation. Int. J. Remote Sens. 2010, 31, 5605–5634.

333. Lu, Z.; Im, J.; Quackenbush, L.; Halligan, K. Population estimation based on multi-sensor data fusion. Int. J. Remote Sens. 2010, 31, 5587–5604.

334. Kressler, F.; Steinnocher, K. Object-oriented analysis of image and LiDAR data and its potential for a dasymetric mapping application. In On segment based image fusion; Springer: Berlin, Germany, 2008; pp. 611–624.

335. Dong, P.; Ramesh, S.; Nepali, A. Evaluation of small-area population estimation using LiDAR, Landsat TM and parcel data. Int. J. Remote Sens. 2010, 31, 5571–5586.

336. Lwin, K.K.; Murayama, Y. Estimation of building population from LiDAR derived digital volume model. In Spatial Analysis and Modeling in Geographical Transformation Process; Springer: Dordrecht, The Netherlands, 2011; pp. 87–98.

337. Qiu, F.; Sridharan, H.; Chun, Y. Spatial autoregressive model for population estimation at the census block level using LiDAR-derived building volume information. Cartogr. Geogr. Inf. Sci. 2010, 37, 239–257.

338. Alahmadi, M.; Atkinson, P.M.; Martin, D. A comparison of small-area population estimation techniques using built-area and height data, Riyadh, Saudi Arabia. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 2014, doi:10.1109/JSTARS.2014.2374175.

339. Sridharan, H.; Qiu, F. A spatially disaggregated areal interpolation model using light detection and ranging-derived building volumes. Geogr. Anal. 2013, 45, 238–258.
340. Tutschku, K. Demand-based radio network planning of cellular mobile communication systems. In Proceedings of the Seventeenth Annual Joint Conference of the IEEE Computer and Communications Societies, San Francisco, CA, USA, 29 March–2 April 1998; pp. 1054–1061.

341. Schneiderbauer, S.; Ehrlich, D. Population Density Estimations for Disaster Management: Case Study Rural Zimbabwe. In Geo-information for Disaster Management; Springer: Berlin, Germany, 2005; pp. 901–921.

342. Akbar, M.; Aliabadi, S.; Patel, R.; Watts, M. A fully automated and integrated multi-scale forecasting scheme for emergency preparedness. Environ. Model. Softw. 2013, 39, 24–38.

343. Hildebrandt, D.; Timm, R. An assisting, constrained 3D navigation technique for multiscale virtual 3D city models. GeoInformatica 2014, 18, 537–567.

344. Slingsby, A.; Raper, J. Navigable space in 3D city models for pedestrians. In Advances in 3D Geoinformation Systems; van Oosterom, P., Zlatanova, S., Penninga, F., Fendel, E., Eds.; Springer: Berlin, Germany, 2008; pp. 49–64.

345. Thill, J.C.; Dao, T.H.D.; Zhou, Y. Traveling in the three-dimensional city: applications in route planning, accessibility assessment, location analysis and beyond. J. Transp. Geogr. 2011, 19, 405–421.

346. Liu, L.; Zlatanova, S. A “door-to-door” Path-Finding Approach for Indoor Navigation. ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 2011, II-4, 45–51.

347. Jamali, A.; Abdul-Rahman, A.; Boguslawski, P.; Kumar, P.; Gold, C.M. An automated 3D modeling of topological indoor navigation network. GeoJournal 2015, doi:10.1007/s10708-015-9675-x.

348. Nagel, C. Spatio-Semantic Modelling of Indoor Environments for Indoor Navigation. Ph.D. Thesis, TU Berlin, Berlin, Germany, 2014.

349. Isikdag, U.; Zlatanova, S.; Underwood, J. A BIM-Oriented Model for supporting indoor navigation requirements. Comput. Environ. Urban Syst. 2013, 41, 112–123.

350. Kim, J.S.; Yoo, S.J.; Li, K.J. Integrating IndoorGML and CityGML for indoor space. In Web and Wireless Geographical Information Systems; Pfoser, D., Li, K.J., Eds.; Springer: Berlin, Germany pp. 184–196.

351. Kim, Y.; Kang, H.; Lee, J. Developing CityGML indoor ADE to manage indoor facilities. In Innovations in 3D Geo-Information Sciences; Springer International Publishing: Cham, Switzerland, 2014; pp. 243–265.

352. Sternberg, H.; Keller, F.; Willemsen, T. Precise indoor mapping as a basis for coarse indoor navigation. J. Appl. Geod. 2013, 7, 231–246.

353. Atilla, U.; Karas, I.R.; Abdul-Rahman, A. A 3D-GIS implementation for realizing 3D network analysis and routing simulation for evacuation purpose. In Progress and New Trends in 3D Geoinformation Sciences; Springer: Berlin, Germany, 2013; pp. 249–260.

354. Atilla, U.; Karas, I.R.; Abdul-Rahman, A. Integration of CityGML and oracle spatial for implementing 3D network analysis solutions and routing simulation within 3D-GIS environment. Geo-Spat. Inf. Sci. 2013, 16, 221–237.
355. Atila, U.; Karas, I.R.; Turan, M.K.; Abdul-Rahman, A. Automatic generation of 3D networks in CityGML and design of an intelligent individual evacuation model for building fires within the scope of 3D GIS. In *Innovations in 3D Geo-Information Sciences*; Springer International Publishing: Cham, Switzerland, 2014; pp. 123–142.

356. Zhang, L.; Wang, Y.; Shi, H.; Zhang, L. Modeling and analyzing 3D complex building interiors for effective evacuation simulations. *Fire Saf. J.* 2012, 53, 1–12.

357. Meijers, M.; Zlatanova, S.; Pfeifer, N. 3D geoinformation indoors: Structuring for evacuation. In Proceedings of the 1st ISPRS/EuroSDR/DPGF International workshop on Next Generation 3D City Models, Bonn, Germany, 21–22 June 2005; pp. 1–6.

358. Schaap, J.; Zlatanova, S.; van Oosterom, P. Towards a 3D geo-data model to support pedestrian routing in multimodal public transport travel advices. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2011, XXXVIII-4/C21, 59–76.

359. Kim, K.; Wilson, J.P. Planning and visualising 3D routes for indoor and outdoor spaces using CityEngine. *J. Spat. Sci.* 2014, 60, 179–193.

360. Dao, T.H.D.; Zhou, Y.; Thill, J.C.; Delmelle, E. Spatio-temporal location modeling in a 3D indoor environment: the case of AEDs as emergency medical devices. *Int. J. Geogr. Inf. Sci.* 2012, 26, 469–494.

361. Christodoulou, S.; Vanvatsikos, D.; Georgiou, C. A BIM-based framework for forecasting and visualizing seismic damage, cost and time to repair. In Proceedings of the European Conference on Product and Process Modelling, Cork, Ireland, 14–16 September 2011.

362. Kemec, S.; Zlatanova, S.; Duzgun, H.S. A framework for defining a 3D model in support of risk management. In *Geographic Information and Cartography for Risk and Crisis Management*; Springer: Berlin, Germany, 2010; pp. 69–82.

363. Jain, S.K.; Singh, R.D.; Seth, S.M. Design flood estimation using GIS supported GIUHApproach. *Water Resour. Manag.* 2000, 14, 369–376.

364. Liu, Y.B.; Gebremeskel, S.; de Smedt, F.; Hoffmann, L.; Pfister, L. A diffusive transport approach for flow routing in GIS-based flood modeling. *J. Hydrol.* 2003, 283, 91–106.

365. Schulte, C.; Coors, V. Development of a CityGML ADE for dynamic 3D flood information. In Proceedings of the Joint ISCRAM-CHINA and GI4DM Conference on Information Systems for Crisis Management: Harbin, China, 4–6 August 2008.

366. Varduhn, V.; Mundani, R.P.; Rank, E. Multi-resolution models: Recent progress in coupling 3D geometry to environmental numerical simulation. In *3D Geoinformation Science*; Springer International Publishing: Cham, Switzerland, 2015; pp. 55–69.

367. Amirebrahimi, S.; Rajabifard, A.; Mendis, P.; Ngo, T. A framework for a microscale flood damage assessment and visualization for a building using BIM—GIS integration. *Int. J. Digit. Earth* 2015, doi:10.1080/17538947.2015.1034201.

368. Sharkawi, K.H.; Abdul-Rahman, A. Towards an efficient city inventory management system for urban authorities in developing countries—The case of 3D change detection. *The Electron. J. Inf. Syst. Dev. Ctries* 2014, 60, 1–13.

369. Pédrinis, F.; Morel, M.; Gesquière, G. Change detection of cities. In *3D Geoinformation Science*; Springer International Publishing: Cham, Switzerland, 2015; pp. 123–139.
370. Qin, R. Change detection on LOD 2 building models with very high resolution spaceborne stereo imagery. *ISPRS J. Photogramm. Remote Sens.* **2014**, *96*, 179–192.

371. GeoSignum. Rotterdam Analyses City Lidar Data with New Technique. Available online: http://www.gim-international.com (accessed on 15 December 2015).

372. Ghassoun, Y.; Löwner, M.O.; Weber, S. Exploring the benefits of 3D city models in the field of urban particles distribution modelling—A comparison of model results. In *Advances in 3D Geo-Information Sciences*; Springer: Berlin, Germany, 2015; pp. 193–205.

373. Hamaina, R.; Leduc, T.; Moreau, G. A new method to characterize density adapted to a coarse city model. In *Information Fusion and Geographic Information Systems (IF and GIS 2013)*; Popovich, V., Claramunt, C., Schrenk, M., Korolenko, K., Eds.; Springer: Berlin, Germany, 2014; pp. 249–263.

374. Ghassoun, Y.; Ruths, M.; Löwner, M.O.; Weber, S. Intra-urban variation of ultrafine particles as evaluated by process related land use and pollutant driven regression modelling. *Sci. Total Environ.* **2015**, *536*, 150–160.

375. Ghassoun, Y.; Löwner, M.O. Comparison of 2D & 3D parameter-based models in urban fine dust distribution modelling. In *Advances in 3D Geoinformation*; Springer International Publishing: Cham, Switzerland, 2016.

377. Rahlf, J.; Breidenbach, J.; Solberg, S.; Næsset, E.; Astrup, R. Comparison of four types of 3D data for timber volume estimation. *Remote Sens. Environ.* **2014**, *155*, 325–333.

378. Piccoli, C. CityEngine for Archaeology. In Proceedings of the Mini Conference 3D GIS for Mapping the via Appia, Amsterdam, The Netherlands, 19 April 2013.

379. De Hond, R. Mapping the Via Appia—3D GIS. In Proceedings of the Mini Conference 3D GIS for Mapping the via Appia, Amsterdam, The Netherlands, 19 April 2013.

380. De Roo, B.; Bourgeois, J.; de Maeyer, P. Usability assessment of a virtual globe-based 4D archaeological GIS. In *Advances in 3D Geoinformation*; Springer International Publishing: Cham, Switzerland, 2016, in press.

381. Gaiani, M.; Gamberini, E.; Tonelli, G. VR as work tool for architectural & archaeological restoration: the ancient Appian way 3D web virtual GIS. In Proceedings of the Seventh International Conference on Virtual Systems and Multimedia, Berkeley, CA, USA, 25–27 October 2001; pp. 86–95.

382. Apollonio, F.I.; Gaiani, M.; Benedetti, B. 3D reality-based artefact models for the management of archaeological sites using 3D Gis: a framework starting from the case study of the Pompeii Archaeological area. *J. Archaeol. Sci.* **2012**, *39*, 1271–1287.

383. Losier, L.M.; Pouliot, J.; Fortin, M. 3D geometrical modeling of excavation units at the archaeological site of Tell ‘Acharneh (Syria). *J. Archaeol. Sci.* **2007**, *34*, 272–288.

384. Katsianis, M.; Tsipidis, S.; Kotsakis, K.; Kousoulakou, A. A 3D digital workflow for archaeological intra-site research using GIS. *J. Archaeol. Sci.* **2008**, *35*, 655–667.
385. Wüst, T.; Nebiker, S.; Landolt, R. Applying the 3D GIS DILAS to Archaeology and cultural heritage projects requirements and first results. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2004, **XXXV/P-B5**, 407–412.

386. von Schwerin, J.; Richards-Rissetto, H.; Remondino, F.; Spera, M.G.; Auer, M.; Billen, N.; Loos, L.; Stelson, L.; Reindel, M. Airborne LiDAR acquisition, post-processing and accuracy-checking for a 3D WebGIS of Copan, Honduras. *J. Archaeol. Sci.: Rep.* 2016, **5**, 85–104.

387. Auer, M.; Agugiaro, G.; Billen, N.; Loos, L.; Zipf, A. Web-based Visualization and Query of semantically segmented multiresolution 3D Models in the Field of Cultural Heritage. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* 2014, **II-5**, 33–39.

388. von Schwerin, J.; Richards-Rissetto, H.; Remondino, F.; Agugiaro, G.; Girardi, G. The MayaArch3D project: A 3D WebGIS for analyzing ancient architecture and landscapes. *Lit. Linguist. Comput.* 2013, **28**, 736–753.

389. Bernknopf, R.; Shapiro, C. Economic assessment of the use value of geospatial information. *ISPRS Int. J. Geo-Inf.* 2015, **4**, 1142–1165.

390. Castelein, W.T.; Bregt, A.; Pluijmers, Y. The economic value of the Dutch geo-information sector. *Int. J. Spat. Data Infrastruct. Res.* 2010, **5**, 58–76.

391. Trapp, N.; Schneider, U.A.; McCallum, I.; Fritz, S.; Schill, C.; Borzacchiello, M.T.; Heumesser, C.; Craglia, M. A meta-analysis on the return on investment of geospatial data and systems: A multi-country perspective. *Trans. GIS* 2015, **19**, 169–187.

392. Carmigniani, J.; Furht, B.; Anisetti, M.; Ceravolo, P.; Damiani, E.; Ivkovic, M. Augmented reality technologies, systems and applications. *Multimedia Tools Appl.* 2011, **51**, 341–377.

393. Çöltekin, A.; Clarke, K.C. A representation of everything. *Geospat. Today* 2011, **1**, 26–28.

394. El-Mekawy, M.; Östman, A.; Hijazi, I. A unified building model for 3D urban GIS. *ISPRS Int. J. Geo-Inf.* 2012, **1**, 120–145.

395. de Laat, R.; van Berlo, L. Integration of BIM and GIS: The development of the CityGML GeoBIM extension. In *Advances in 3D Geo-Information Sciences*; Springer: Berlin, Germany, 2011; pp. 211–225.

396. Isikdag, U.; Zlatanova, S. Towards defining a framework for automatic generation of buildings in CityGML using building information models. In *3D Geo-Information Sciences*; Springer: Berlin, Germany, 2009; pp. 79–96.

397. El-Mekawy, M.; Östman, A.; Hijazi, I. An evaluation of IFC-CityGML unidirectional conversion. *Int. J. Adv. Comput. Sci. Appl.* 2012, **3**, 159–171.

398. Biljecki, F.; Arroyo Ohori, K. Automatic semantic-preserving conversion between OBJ and CityGML. In Proceedings of the Eurographics Workshop on Urban Data Modelling and Visualisation 2015, Delft, The Netherlands, 23 November 2015; pp. 25–30.

399. Kumar, K.; Saran, S.; Kumar, A.S. CityGML based interoperability for the transformation of 3D data models. *Trans. GIS* 2016, in press.

400. Müller Arisona, S.; Zhong, C.; Huang, X.; Qin, H. Increasing detail of 3D models through combined photogrammetric and procedural modelling. *Geo-Spat. Inf. Sci.* 2013, **16**, 45–53.
401. Martinović, A.; Knopp, J.; Riemenschneider, H.; van Gool, L. 3D all the way: Semantic segmentation of urban scenes from start to end in 3D. In Proceedings of the 28th IEEE Conference on Computer Vision and Pattern Recognition, Boston, MA, USA, 7–12 June 2015; pp. 4456–4465.

402. Rautenbach, V.; Bevis, Y.; Coetzee, S.; Combrinck, C. Evaluating procedural modelling for 3D models of informal settlements in urban design activities. *South Afr. J. Sci.* **2015**, *111*, doi:10.17159/sajs.2015/20150100.

403. Jung, H.; Lee, K.; Chun, W. Integration of GIS, GPS, and optimization technologies for the effective control of parcel delivery service. *Comput. Ind. Eng.* **2006**, *51*, 154–162.

© 2015 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/4.0/).