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Article

Characterizing 3D City Modeling Projects: Towards a Harmonized Interoperable System

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Abstract: 3D city models have become common geospatial data assets for cities that can be utilized in numerous fields, in tasks related to planning, visualization, and decision-making among others. We present a study of 3D city modeling focusing on the six largest cities in Finland. The study portrays a contradiction between the realized 3D city modeling projects and the expectations towards them: models do not appear to reach the broad applicability envisioned. In order to deal with contradiction and to support the development of future 3D city models, characteristics of different operational cultures in 3D city modeling are presented, and a concept for harmonizing the 3D city modeling is suggested.

Keywords: 3D city modeling; 3D GIS; 3D geoinformation; interoperability; socio-technical system

1. Introduction

A digital three-dimensional (3D) city model describes the geometry and structure of an urban environment [1]. The definition of what constitutes a 3D city model still remains ambiguous and unclear [2] as the term has been applied in literature to a wide spectrum of different cases, ranging from 3D reconstruction [3] to semantic models [4]. Commonly, a 3D city model is understood to combine non-geometric data with the 3D geometry of urban objects [4], such as roads [5], trees [6], terrain, and 3D building models. These models are typically built through 3D reconstruction and data integration, for example merging photogrammetry [7] or laser scanning [8] data with geographic information systems (GIS) data such as building footprints and IDs [2].

3D city modes can be utilized in numerous fields, in tasks related to planning, visualization, and decision-making among others. Biljecki et al. [2] identified more than a hundred different applications for 3D city models. In addition, 3D city models can be seen as an enabler in the smart city paradigm [9], operating as a user interface to the systems of a modern urban environment, acting as a platform for cooperation [10], and as a platform for services [11]. 3D city models have also been envisioned as virtual collaborative platform for individual citizens [12].

Along with advancements in data acquisition (e.g., [13]), 3D reconstruction [3], and applications [2], 3D city models have become common geospatial data assets for cities. A comprehensive study by [14] already identified over one thousand 3D city models worldwide.

The discussion on 3D city models is further complicated by the amount of different platforms available for 3D city modeling. 3D city models are applied in professional GIS/CAD tools, virtual globes, or 3D game engines. GIS/CAD platforms are typically targeted at professional users—such as city planners, architects, surveyors, etc.—and not at the general public. Virtual globes are 3D web viewers for geospatial information, where the user can freely move around and change viewing angles (e.g., Google Earth, Google LLC, Mountain View, CA, USA). As user-friendly, browser-based systems, virtual globes are commonly used to target public audiences. Virtual globes combine features from GIS/CAD platforms (e.g., geographical coordinates) and game engines (e.g., higher visual realism or interactive and game-like elements). 3D game engines are flexible application development platforms that can be used to build more specific (but usually one-off) online and/or offline software titles that require the highest visual realism (real-time rendering of light and shadows), an interactive user experience, and maximized user engagement. In addition to their use in entertainment, they are being applied to visualization in city planning and architecture. Game engine applications are rarely tied to any geographic coordinate system [15–17].

The interoperability of 3D city models and especially the integration of 3D GIS and building information (BIM) models has been a significant research question [4,18–25]. One of the aims has been in developing a process where the building data of a 3D city model would be updated using BIM models of new buildings. BIM data is typically exchanged using the Industry Foundation Classes (IFC) standard. IFC is a semantic model like CityGML, a standard exchange format in 3D GIS, but it is restricted to building data and focuses on the structural information related to the construction and design of buildings [19]. Numerous conversion tools have been developed but a robust two-way conversion between IFC and CityGML models still remains unsolved even in the scale of single buildings of fairly simple structures [23]. Moreover, 3D game engines lack the support for both CityGML and IFC standards since they have not been optimized for efficient visualization required in immersive applications [12,19,26]. On the other hand, common standards and formats (e.g., Collada, OBJ, and FXB) in 3D computer graphics that focus on powerful visualization lack the semantic structures and descriptions used in both IFC and CityGML [4]. Despite numerous research activities the interoperability of 3D city models remains as a challenging task and is still hindered by many issues, such as the ambiguities and differences in modeling, differences in perspectives, missing guidelines, challenges in data conversion and georeferencing, and problems in data quality [4,23–25,27]. So far, very few if any contributions have been published focusing on the integration of 3D GIS, BIM, and computer graphics models. However, these three categories are noted in the literature and can be seen as a topic for further research to achieve more comprehensive overview of 3D city modeling.

Finnish cities have been active in 3D city modeling, ranging from limited area pilot projects [28] to citywide modeling efforts [29]. Some of these projects have been reported in research literature (e.g., [12]) and in university theses (e.g., [30,31]). While some organizations are aiming to coordinate 3D city modeling activities in Finland [32] and have carried out surveys on the topic [33], no recent review of 3D city modeling in Finland exists to this day. On a larger scope, the status of 3D national mapping within seven European national mapping agencies, including the National Land Survey of Finland, has been reviewed by [34].

Besides technical solutions, technology can be seen as a human construct that requires human action, and social structures and organizations in order to function [35,36]. Cities are socio-technical systems [37] and therefore 3D city modeling is affected both by societal aspects of the cities and the emerging technology: processes in the cities are dependent on the available ICT tools [38]. At the same time, emerging tools may change the way organizations operate, altering their processes [39]. In order to create better understanding of the processes taking place and affecting the development of 3D city modeling, it is central to take into account that 3D city models are part of a socio-technical system and result of it. Referring to [35], there are certain elements—such as changes in user behavior, in regulations and guidelines, and in cultural understanding—which reveal a shift in socio-technical systems.

We present a study of 3D city modeling, focusing on sample projects in the six largest cities in Finland. Our study is divided into two parts: The first part is an overview study, focusing on the outcomes of the sample projects. In order to form the overview and support the analysis and aims, the following indicators were selected for the content analysis: (1) the used platform; (2) data accessibility;

(3) regional data coverage; and (4) the utilization of as-planned information. Available sources maintained by the cities themselves are used to obtain an overview of current projects. The second part focuses on explanatory internal drivers and factors. By carrying out interviews with city authorities and experts in the six reference cities in Finland, we aim to understand what explains the observations.

2. Materials and Methods

2.1. An Overview Study of 3D City Modeling Activities in Finland

To form an overview of 3D city modeling activities in Finland, 19 different 3D city model projects were selected from the six largest cities in Finland: Helsinki, Espoo, Tampere, Vantaa, Turku, and Oulu. To identify the latest and most relevant modeling projects, public information about the 3D city modeling activities was extensively screened. We included data sets maintained by geoinformation practitioners in cities, as well as some notable individual projects that have been executed by private contractors.

For the overview study, a set of indicators was selected: the used platform, data accessibility, regional data coverage, and the utilization of as-planned information. These selected indicators are reoccurring and unambiguous in the sample data, and can be considered essential for the functionality and usability of the 3D city models. Analyzing the used platform gives insight on the technical solution utilized in the case project and further determines aspects of the city model that can be considered important such as the level of collaboration and communication, interaction, visualization, interoperability, user experience, geo-referencing, and type of data the platform enables [26,40–42]. Analyzing the data accessibility offers information about the targeted audience of the 3D city model. Is the data available only for internal use, or for public use as well? The latter increases the collaboration and contribution potential [41]. Regional data cover determines whether the utilization potential of the 3D city model is citywide or only limited to a specific part of it. Analyzing the utilization of as-planned information gives understanding about the level of integration of as-planned data (e.g., BIM models) to the 3D city model (typically based on as-built 3D GIS data). This integration extends the temporal scale of the model and could enable numerous applications [24] for the project.

In this study, we included projects that contained, at minimum, 3D building data and other relevant urban information. In addition, answers to the following questions had to be available:

1. What is the used platform? As platforms, we considered software solutions that can provide 3D city models for its users and enable a workspace for collaborators, including solutions for maintaining 3D geoinformation (GIS/CAD software), application development platforms (3D game engines), and visualization software (virtual globes).
2. Is the 3D city model publicly viewable and/or downloadable as open data?
3. What is the regional coverage of the model?
4. Does the 3D city model project utilize as-planned information (e.g., BIM)?

In this study, 3D models focusing on single buildings or indoor spaces were excluded. In addition, 3D models of limited areas, such as individual sites in the architecture, engineering and construction (AEC) industry, were largely omitted as these projects often fall more into the domain of building information modeling (BIM) rather than 3D city modeling. The final selected activities are listed in following table, Table 1.

Table 1. A list of selected 3D city modeling activities within six largest cities in Finland.

City	Project
Espoo	3D city model data Mission Leppävaara Otaniemi lighting simulation Tapiola
Helsinki	Helsinki 3D+ information model Helsinki 3D+ mesh model 3D city model data Oulunkylä 2030
Oulu	3D city model data VirtualOulu Hiukkavaara 3D model SmartOulu
Tampere	3D city model data
Turku	3D city model data 3D model of Turku campus and science park area
Vantaa	3D city model data Kivistö Minecraft Myyrmäki

2.1.1. The City of Espoo

The city of Espoo currently maintains its base map data using Locus (Trimble Inc., Sunnyvale, CA, USA) [43]. 3D city modeling is tied to the base mapping process and includes collecting 3D assets, such as building models, trees, light poles, digital terrain and surface models, and underground structures [44]. A part of this dataset is distributed openly with a creative commons license (CC BY 4.0) in the Helsinki Region Infoshare (HRI) portal and via the city's web-based map service. WMS and WFS interfaces are also maintained. Openly available 3D data contains building models (LoD1) in SketchUp format, digital terrain models as DWG files, and 3D point clouds in LAZ format [45].

Espoo has also carried out a number of limited pilot projects that utilize 3D city models, for example, the Mission Leppävaara pilot utilizes CityPlanner [46], a participative planning platform developed by Agency9 (AB, Stockholm, Sweden) (Figure 1). The main goal of the project is to encourage citizens to participate in the urban planning process. The used web-based platform enables citizens to study the 3D model of the Leppävaara district, review a set of planned new buildings, give feedback, and support the suggestions made by others [47].

The Unity (Unity Technologies SF, San Francisco, CA, USA) game engine [48] is utilized in a virtual city model of the Tapiola district. The area of Tapiola has been split into several browser-based scenes that are made accessible through the Unity Webplayer, allowing navigation with a pedestrian avatar [28]. Another Unity-based example, the Otaniemi lighting simulator, contains navigation features similar to those of the Tapiola model but includes additional functionality for lighting design. The user can add different types of outdoor luminaires to the model and study their impact on the lighting of the environment [49].

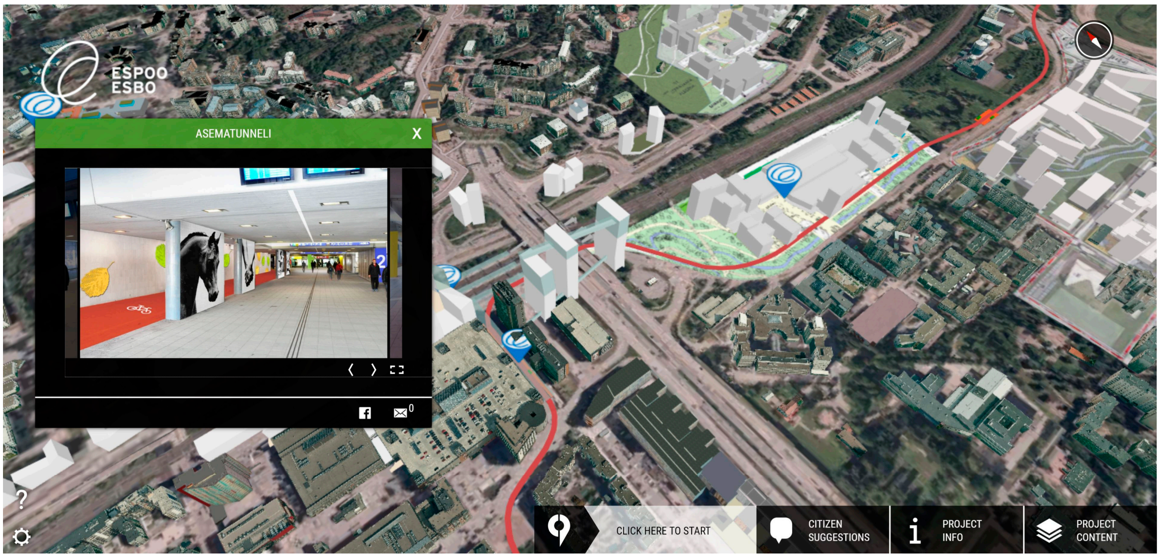

Figure 1. Mission Leppävaara pilot aims to encourage citizens to participate in the urban planning process within the Leppävaara district in Espoo [47].

2.1.2. The City of Helsinki

The city of Helsinki has a long tradition in 3D city modeling with the first 3D virtual models of the city being produced in the 1980s [31]. As a part of a recent 3D city modeling project, Helsinki 3D+, the city has released a CityGML-based semantic 3D city model (Figure 2) and a more visually detailed 3D mesh model. The semantic 3D city model is the first citywide model in Finland that conforms to the open CityGML standard [50]. The model geometry and textures were produced using airborne laser scanning (ALS) and oblique imagery data. The textured CityGML (LoD2) building data is openly available through HRI [51]. The CityGML model can also be accessed via a Cesium-based [52] web viewer [53]. The 3D mesh model is based on oblique imagery and was produced using ContextCapture (Bentley Systems Inc., Exton, PA, USA) [54]. It can also be downloaded in 3XM and OBJ formats [51]. Helsinki also provides access to the 3D mesh model via a Cesium-based web viewer [55]. The city has tried to encourage people to use the new 3D city models by mapping out potential use cases and launching several pilot projects [56].

Apart from the aforementioned models, the city maintains geospatial base map data in MicroStation (Bentley Systems Inc., Exton, PA, USA) [57]. An additional dataset of LoD1-type 3D building models is openly available in SKP and KML/KMZ formats [58]. The ALS point cloud and digital terrain model are distributed via Helsinki public web map service [59] and HRI [60]. The Helsinki data sets are made available with a Creative Commons license (CC BY 4.0).

In addition to these datasets, over the years Helsinki has carried out several limited pilot projects utilizing 3D city models. For example, the Oulunkylä 2030 project utilizes the new 3D city model assets in an urban development project in the Oulunkylä district. In a web application based on a Unity game engine, the users can give ideas and feedback on three different optional plans for a new urban infill project [61].

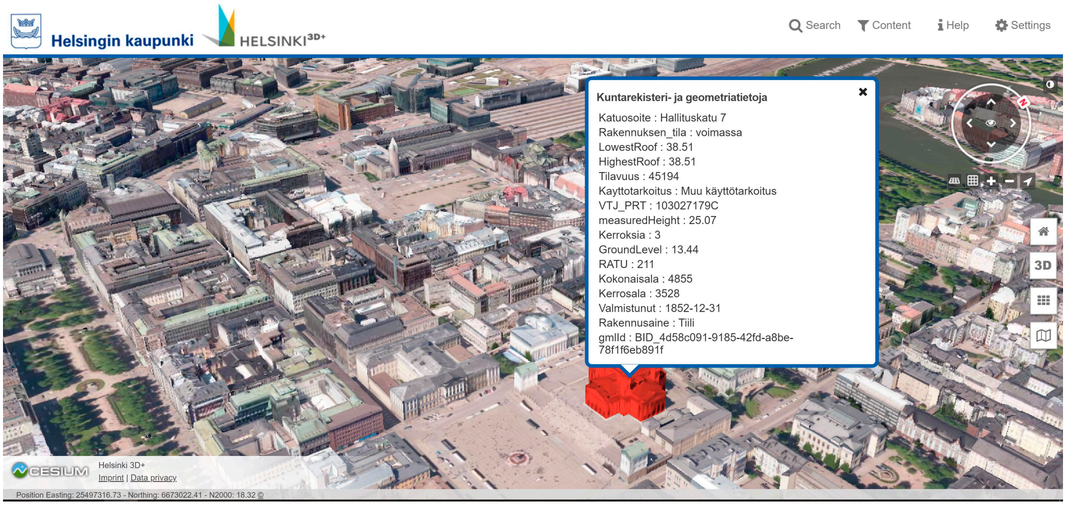

Figure 2. Helsinki 3D+ information model is the first citywide model in Finland that conforms the open CityGML standard [53].

2.1.3. The City of Oulu

A web-based multi-user 3D environment (Figure 3) depicting the center of Oulu was released in 2014 [12]. The user can navigate a textured 3D model using either a birds-eye view or a street level view and perform simple interactions, such as browse historical information about buildings. The building models are game-engine style mesh models, created by various companies from laser scanning and photographic data. The models are available as public domain material that is downloadable from the project website [62]. Currently, the models are being used in the development of a second version of the browser-based VirtualOulu as a research effort. In addition, the modeled buildings are applied in research projects regarding virtual reality, augmented reality, and ubiquitous computing, as well as being used as teaching material in game-engine programming.

The city of Oulu is also developing a larger, less-detailed 3D city model for architecture and city-planning. The model utilizes Locus as a data source, exporting files as SketchUp models [63].

The Oulun Hiukkavaara project consist of two separate applications based on game engines where the users can study and give feedback about a two urban infill projects in the Hiukkavaara residential district in Oulu. Both of these web-based applications are built on a Unity game engine and focus on the visualization of new city plans [64].

SmartOulu is a MAPGETS-based (FCG City Portal Oy, Helsinki, Finland) [65] web application where the users can view the new urban development investment in the city of Oulu using a 3D environment. The purpose of the application is to help the users to identify and develop innovative future investments and improve the timing of resources [66].

Figure 3. VirtualOulu is a web-based collaborative 3D environment depicting the center of Oulu [62].

2.1.4. The City of Tampere

Tampere uses Novapoint (Trimble Inc., Sunnyvale, CA, USA) [67], Quadri (Trimble Inc., Sunnyvale, CA, USA) [67], and AutoCAD (Autodesk Inc., Mill Valley, CA, USA) [68] to maintain their geospatial data, including 3D building data, digital terrain model, and information about the lighting, vegetation, and building façades. The 3D model of Tampere is available via the public map index service Oskari. The individual model segments can be viewed directly (through a web viewer by Viasys VDC), and downloaded in DWG format [69]. Many urban development projects in Tampere have utilized 3D city model data, for example, it was used in visualizing the Five-star City Centre development program and in an urban infill project in the Tammela district [70].

2.1.5. The City of Turku

Turku maintains their geospatial data in Locus and data distribution is channeled through the city's website. 3D city modeling data—such as that found in an ALS point cloud digital terrain model—can be ordered directly from the city. To this date, Turku is the only one of the six largest cities in Finland that has not opened its city model datasets that give full coverage of the city [71].

In addition, Turku has published a 3D model of Turku Campus and Science Park area for the Turku Future Hackathon competition. The model can be downloaded via the Lounaistieto web service [72] with a CC BY 4.0 license and viewed online via the Sova3D (Sova3D Oy, Helsinki, Finland) web platform [73]. The 3D model consists of LoD2-type textured 3D buildings, a digital terrain model, and trees visualized as colorized ALS point clouds.

2.1.6. The City of Vantaa

Vantaa maintains their geospatial data in Microstation. LoD1 and LoD2 building models are maintained continuously with the base map and are openly available in SKP and KML formats with a CC BY 4.0 license from the HRI web service. KML files also contain semantic information about the buildings such as their type, ID, year of completion, and address [74].

The city of Vantaa has piloted the use of a highly detailed city model in the Kivistö district for the Housing Fair Finland event. In addition to as-built information, this Unity application uses the as-planned information of newly built houses converted from BIM models [75].

Vantaa has also released a model of the city in the Minecraft format where the city is split into seven city-district scenes that can be downloaded from HRI and imported into Minecraft. The Minecraft scenes are based on geospatial data, such as digital terrain models, 3D building models, and land-use data maintained by the city of Vantaa. As a popular sandbox game, Minecraft offers a familiar environment, especially for younger people, in which to explore and experience the urban space [76].

Myyrmäki was a recent experimental browser-based game where the public could vote for their favorite options for decorating a public space in the Myyrmäki district. The game utilizes a photorealistic 3D city model in a Unity web application. The results from this game will be used to support the later design of the targeted public place [77].

As an ongoing development, the city of Vantaa has initiated a project aiming to produce a holistic system for land use, planning, and construction, integrating 3D GIS, document management, and permit processes [78].

2.2. Expert Interviews

As an additional data source, we interviewed city representatives of the selected cities. The informants were selected by asking the city authorities to name the representatives responsible for 3D city modeling. Thus, the city authorities could define who they considered as suitable informants within city modeling in their organizations. In addition, some external consultants were invited by two reference cities, Vantaa and Oulu, to join the interview as informants. The interviews were carried out in the spring and summer of 2016, and all the interviews were voice recorded and transcribed.

The lengths of the interviews varied from 60 min to 143 min. The total amount of informants was 34. The status and background of the informants varied from GIS management, city surveying, city planning, and urban development to supervisory control of building. The numbers of participants in the interviews are listed in Table 2.

Table 2. Participants in the interviews.

Reference City	Number of Informants Representing the City Organization	Number of Informants not Representing the City Organization	Number of Interviewers	Total Number of Participants
Espoo	6		2	8
Helsinki	1		3	4
Oulu	5	1	2	8
Tampere	4		4	8
Turku	9		3	12
Vantaa	4	4	3	11

The interviews were conducted by using a semi-structured interview plan, but the content of the interviews varied according to the situation in the city, and the expertise and emphasis of the informants. As the study focuses on internal drivers, in the analysis we emphasize the views and comments that the city representatives considered important. The semi-structured interview plan consisted of following:

1. Description of the current situation in the reference city. *What is the current situation of 3D city modeling in the city you are representing?*
2. Expectations regarding 3D city models. *Which tasks should the future 3D city models serve?*
3. Expected users. *Who are the expected users of the 3D city model?*
4. Key factors in the development of 3D city modeling. *What can hinder or enhance the development?*
5. Data. *What kind of data is needed to implement a 3D city model?*
6. Visualization. *How should 3D city models be visualized?*

The analysis of the interviews is based on the transcriptions. The interviews include the views of the city representatives related to the status and significance of 3D city modeling in their city organization. By using thematic structuring, data was divided into two themes: firstly, the internal drivers and potential of 3D city modeling, and secondly, the internal challenges and barriers for development of 3D city modeling.

3. Results

3.1. Overview Study

The selected 3D city models were analyzed, focusing on the selected indicators: the platform utilized, data accessibility, regional data coverage, and the utilization of as-planned information. A summary of this analysis is presented in Table 3.

Table 3. A summary of the analyzed 3D city modeling activities based on the selected indicators.

City	Project	Used Platform(s)	Data Accessibility		Full City Data Coverage	Utilization of As-Planned Information
			Data Publicly Viewable	Data Publicly Downloadable		
Espoo	3D city model data	Locus	-	X	X	-
	Mission Leppävaara	CityPlanner	X	-	-	X
	Otaniemi lighting simulation	Unity	X	-	-	X
	Tapiola	Unity	X	-	-	X
Helsinki	Helsinki 3D+ information model	Cesium	X	X	X	-
	Helsinki 3D+ mesh model	Cesium	X	X	X	-
	3D city model data	Microstation	-	X	X	-
	Oulunkylä 2030	Unity	X	-	-	X
Oulu	3D city model data	Locus	-	X	X	-
	VirtualOulu	Unity, Unreal Engine	X	X	-	-
	Hiukkavaara 3D model	Unity	X	-	-	X
	SmartOulu	MAPGETS	X	-	X	X
Tampere	3D city model data	Novapoint, Quadri, AutoCAD, Viasys VDC	X	X	X	-
Turku	3D city model data	Locus	-	-	X	-
	3D model of Turku campus and science park area	Sova3D	X	X	-	-
Vantaa	3D city model data	Microstation	-	X	X	-
	Kivistö	Unity	X	-	-	X
	Minecraft	Minecraft	-	X	X	-
	Myyrmäki	Unity	X	-	-	X
Total	19	13	13	10	10	8

The used platforms have a big variance: 13 different platforms were used for the 19 studied models. The used platforms included GIS/CAD software (e.g., Locus and Microstation), virtual globes (e.g., Cesium, CityPlanner, Sova3D, MAPGETS), and game engines (e.g., Unity, Unreal Engine). The division per platform type is pictured in Figure 4.

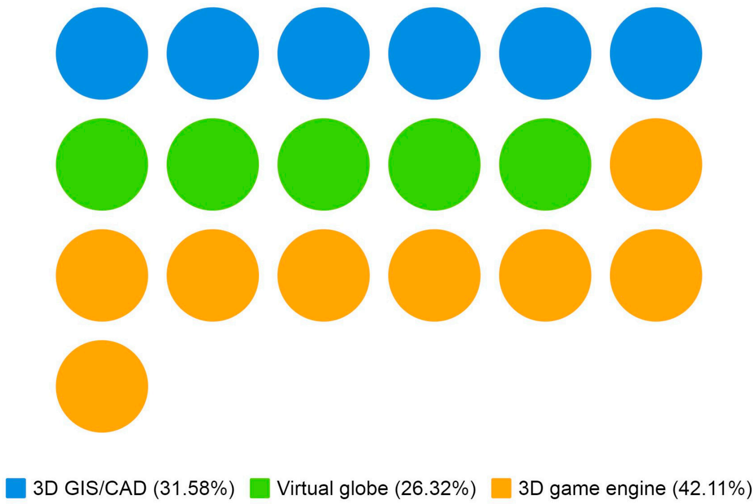

Figure 4. The division of 3D city models per platform type among the studied 19 projects.

In all six cities the maintenance and upkeep of 3D city models was tied to the statutory base mapping process. Understandably, the GIS/CAD software applied for 3D city models was often the one used for their base mapping processes. All of the targeted cities used at least one GIS/CAD solution primarily meant for internal and professional use within the city organization. All of these GIS/CAD platforms fully supported geographic coordinate systems with the focus more on information and/or illustrative visualization than on photorealistic visualization [79] based applications.

Some of the software solutions applied in Finland were more or less unique and have not (at least not yet) seen wide adoption globally. The studied sample of 3D models contained a wide variety of different levels of detail, ranging from simple block models (loosely equivalent to LoD1 of CityGML) to highly detailed photorealistic models containing modeled facades (loosely equivalent to LoD3 of CityGML). In many cases, the 3D model data maintained by the city was used as an input or reference data in virtual globe and 3D game engine-based projects that focused on more specified applications (e.g., Otaniemi Lighting simulation) and/or for broader audiences (e.g., Mission Leppävaara). The 3D city models based on game engines had the highest level of verisimilitude due to the more advanced real time rendering of light and shadows but were limited to local coordinate systems and rarely took any benefit of semantic information. In addition to more detailed visuals, the 3D game engine-based models had clear emphasis on game-like interaction and immersion with the goal in engaging users to collaborate and explore the models even on a pedestrian level. Considering visualization, the models based on virtual globes fall in between the GIS/CAD and 3D game engines mainly due to the performance constraints set by the web browser technologies.

Data accessibility: A total of 13 out of the 19 (63%) city models could be viewed via a web-based viewer application being used to visualize the data. This was realized either via separate web plugins and viewers or, in the case of virtual globes, natively by the platform itself. A total of 10 out of the 19 (53%) city models studied were distributed freely over the Internet. The publicly distributed 3D data commonly consisted of ALS-derived (and periodically updated) 3D building models and digital terrain models. The city of Turku was the only city that did not openly distribute a 3D city model of the whole city. The data distribution was handled either through the city's own web map portal, a project-specific website, or via centralized open data portals like the HRI website for the capital region of Finland. Notably none of the cities offered any original raw data that somewhat hinders the possibilities to freely develop the models further. In all of the cases, the shared data had gone through some level of processing.

Regional data coverage: A total of 10 out of the 19 (53%) city models covered the full regional area of the city, with each of the studied cities maintaining at least one citywide model. Notably the Minecraft model in Vantaa was the only 3D game engine-based city model that had citywide data coverage.

The utilization of as-planned information: A total of eight out of the 19 (42%) city models utilized as-planned information, such as detailed BIM models (e.g., the Kivistö project in Vantaa), or other types of information, such as architectural plans (e.g., SmartOulu in Oulu or Mission Leppävaara in Espoo). Six out of eight game engine-based models utilized as-planned information. For virtual globes, two out of five utilized as-planned information. We could not find evidence of the utilization of as-planned models on the GIS/CAD-based platforms.

3.2. Interviews

In the interviews, both the perceived potential of the 3D city models and the barriers that hinder their adoption were touched upon. Generally, 3D city models were considered to have the potential to enhance communication and collaboration, both inside and outside the city organization. Increased visuality through using 3D was seen as a key element in enhancing the interaction and trust between different stakeholders. The ability to demonstrate the impact of decisions and to include all relevant stakeholders in the co-design and decision-making processes were seen as the most anticipated benefits when utilizing 3D city models. In many cases a 3D model was noted to be unambiguous and generally simpler to comprehend than a 2D representation, and the level of detail could be adapted according to the need.

3D city models could enable open and multi-purpose services. We noted that the informants envisioned 3D models as scalable, flexible, and multi-purpose digital platforms that were not only for internal use. The 3D city models were seen to be able to serve as a forum for integrating city services and information about the city, and enabling interaction between citizens and civil servants.

This contained the notion of a digital twin of the real city: A space where all the citizens could intrinsically act. This included the idea of enhanced citizen participation, planning as co-creation, and the role of crowdsourcing in managing the city. The 3D city model was even imagined as a virtual place where everyone could create their own vision of the city. Overall, (1) interactivity and (2) the possibility to gain real-time information about the processes and services of the city were deemed important; these two functions would make the 3D city meaningful to the citizens. A couple of informants also pondered on the near-future potential of virtual reality and augmented reality technologies, and the related wearable computing: If these were adopted by large numbers of people and become a part of everyday urban life, the meaning of 3D city models would be increased drastically as the boundaries between physical and digital cities would be blurred (see also [80]).

In addition, the interview results showed that 3D city models have the potential to enhance data and lifecycle management within cities. 3D city models were seen as platforms for managing all the data that could support the design, planning, maintenance, and decision-making processes across all the different municipal sectors.

When discussing the barriers, the informants stated that up-to-date guidelines and policies were missing or that the existing guidelines were not followed. Ambiguous terminology, a lack of coordination and leadership, and the slow adaptation of standards frequently crippled communication and collaboration. Stakeholders inside and outside city organizations were a heterogeneous group of users that had varying needs, expectations, and views towards 3D city modeling. Legislation was not up to date either. Copyright, data ownership, and privacy issues were seen as unclear and unsolved issues.

In addition, the lack of expertise was seen to result in an incapacity to recognize the need for 3D city modeling, and hence to define the requirements for 3D city modeling. This was manifested in failed procurement processes related to 3D city models. Hence, more capacity building was required for the cities to drive 3D city modeling to its full potential. In many cases, the cities would have wanted to be more independent from the private contractors and consultants. The role of cities was seen as profound: In general, they were seen as the ones that should build and keep up the basic 3D city model, which companies could, then, use for their own purposes and create, for example, service layers targeted for particular users. Furthermore, some informants thought that the lack of suitable revenue generation models prevented fruitful cooperation between cities and companies that could play a pivotal role in creating the new services needed.

Among the informants there existed a clear consensus that the 3D city models were neither scalable nor easy enough to modify. This was explained by the notion that the future uses for 3D city models are seen to be hard to predict and the group of users is heterogeneous.

4. Discussion

The informants stated several applications for 3D city models. They were envisioned as digital platforms that serve cities, organizations, and citizens by enhancing communication and collaboration, and enabling open and multi-purpose services, as well as by enhancing data and lifecycle management within cities.

The studied projects had a large variance in all of the studied aspects: technical solutions, data accessibility, regional data coverage, and the utilization of as-planned information. Therefore, the reference 3D city model projects were more likely to only serve a limited number of purposes, or pilot modeling in a limited area, rather than act as a general platform for the city. In general, the interview results confirmed with this observed fragmentation.

However, the interview results showed that, in general, this had not been the intent in cities. In these cases, the expected potential of current city models had not been fulfilled.

4.1. Characteristics in 3D City Modeling Projects

To explore the differences of the fragmented city modeling projects, we place them to three partially overlapping categories (3D GIS, BIM and computer graphics) that appear in the literature (Table 4). Each of the studied 3D city models is influenced by at least one of these three. A total of 11 out of the 19 projects contained elements of spatially oriented 3D GIS culture, nine out of 19 projects were related to visually oriented computer graphics culture, and eight out of the 19 projects were closely related to BIM. The studied 3D city model cases can be classified into their respective operational culture or combination of multiple cultures (Figure 5). By doing so it becomes evident that none of the studied sample projects clearly overlaps with all three categories. In other words, completely harmonized 3D city model was not found among the sample data.

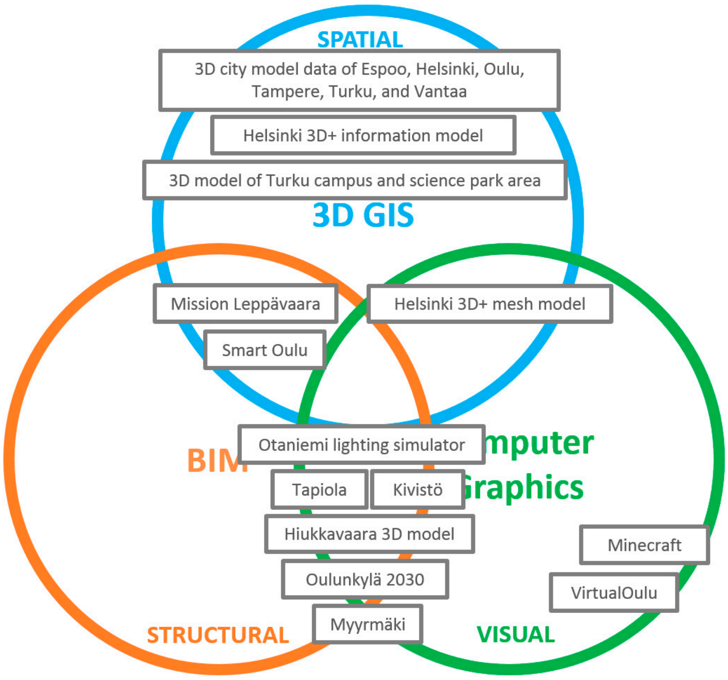

Figure 5. The studied 3D modeling activities in three categories representing distinct operational cultures.

Combining the studied 3D city modeling activities and literature, we can recognize typical characteristics for each operational culture (Table 4). Every category has its own unique perspective that leads to different 3D city model realizations.

Table 4. The characteristics of the operational cultures in 3D city modeling.

3D GIS	BIM	Computer Graphics
Focus in real world data [18,22]	Focus in as-planned data [18,24]	Real world and as-planned data
Simplified model complexity (geometry and semantics) [12,18,21]	High model complexity (geometry and semantics) [21]	Intermediate model complexity (geometry) [12]
Citywide data coverage	Local data coverage	Local data coverage
Global coordinate systems [21,25]	Limited use of coordinate systems [18,24,25]	Limited use of coordinate systems [81]
Database approach (maintained models) [22]	Life-cycle approach [18,24]	Felixible application development approach [12,16,81–83]
Automated or semi-automated modeling (geometry) [3]	Manual modeling [21]	Manual modeling [12,81,82]
		User engagement (immersion, interactivity and multi-user environments) [12,82]
		Visual realism (real-time rendering) [12]

4.2. The Concept for Harmonizing 3D City Modeling

Using the defined characteristics, we outline a concept (Figure 6) that aims to harmonize 3D city models by combining the perspectives of all three operational cultures by integrating their key characteristics into one interoperable system. Developing the level of interoperation and integration reduces fragmentation and enables new applications.

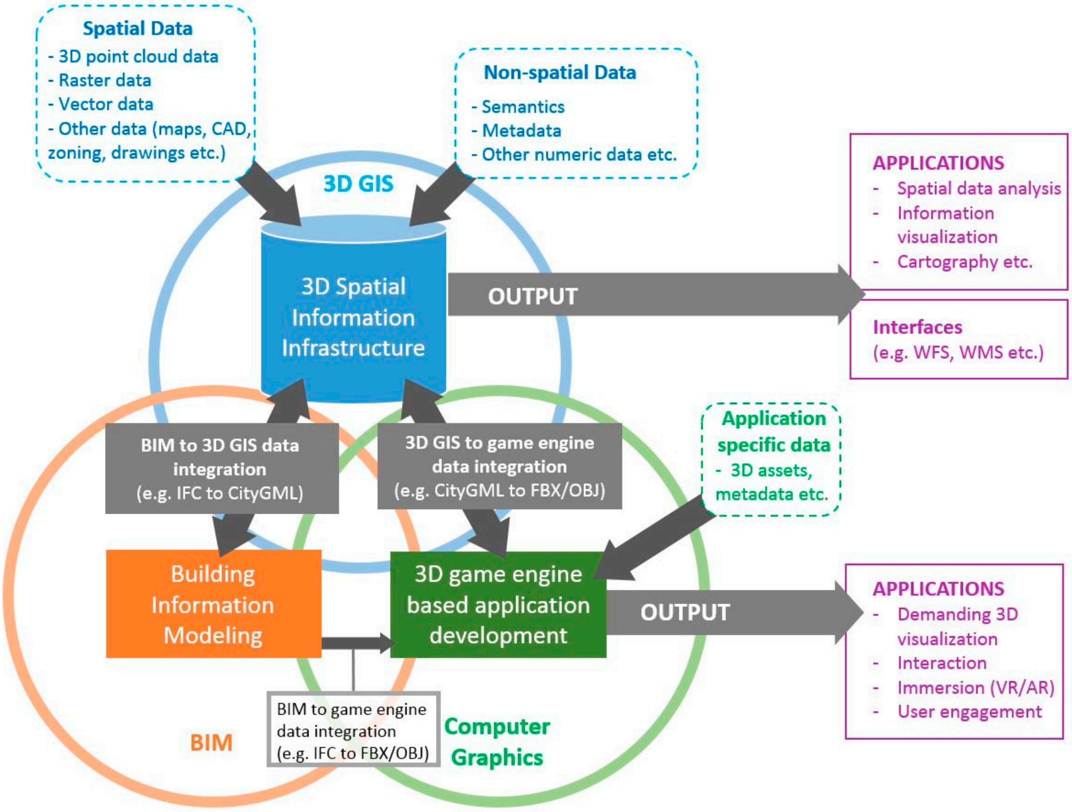

Figure 6. The concept for harmonizing 3D city modeling.

In the core of this concept is the 3D spatial information infrastructure that is responsible for maintaining, managing, integrating and globally geo-referencing the spatially applicable data from multiple data sources: spatial data, non-spatial data, and BIM data. The infrastructure supports common interfaces (e.g., WFS, WMS etc.) and applications that require spatial data analysis and queries, information visualization, and cartography.

The building data of 3D city model is updated from IFC models not only in the case of new buildings but also throughout the life-cycle of a building. A bidirectional integration is needed for BIM to take benefit of 3D GIS data and expand the spatial scale of the models beyond single buildings or sites. Another key element in this concept is implementing the bidirectional data integration between the 3D GIS and 3D game engines. Moreover, the required spatial 3D data must be converted into polygon mesh model formats (e.g., FBX or OBJ) and optimized to properly function as 3D assets in 3D game engines. Applications that require powerful 3D visualization and interaction, focus on immersive experiences (e.g., VR/AR applications) or user engagement (e.g., applications for public participation) on multiple computing platforms (e.g., mobile, desktop, VR/AR etc.) benefit greatly from game engine technology. The bidirectional integration is necessary for feeding data based on user input from the applications back into the spatial database. In addition, in some specific applications that require the highest model complexity (e.g., merging indoor and outdoor data) it is necessary to be able to convert the BIM models directly into the 3D game engine environment without the need to integrate the data first into the spatial database and overly simplifying it in the process.

4.3. Limitations and Suggestions for Further Research

In addition to the geographic limits, the presented overview study is limited to the projects that are documented in publicly available sources. This also limited the scope of features studied in projects, as only features that were comparable were selected as indicators.

Regarding the interviews, the general limitations of interview studies apply, such as subjective views and the background of the informants, conforming into popular opinion, generalization, informants tendency to share information they believe to be true while that being a matter of perception. In addition, anonymity was not guaranteed for the informants that might cause a social desirability bias. In the analysis of interviews, the background of an informant had no special emphasis in the design and analysis of the interview. This was partly due to the variety of ways in how 3D modeling has been organized in the reference cities. Systematic analysis based on the background of the informant would have required a study on the organizational structure of each reference city. Hence the informants were not divided into groups by the field or profession they represented but treated as representatives of the 3D city modeling of the city they represented.

Further research topics include focusing into developing a framework for national 3D spatial infrastructure, focusing on studying the 3D city models as a product of organizational development, and developing a technical demonstration of a 3D city model that is interoperable with all three categories.

5. Conclusions

This paper presents a study of 3D city modeling projects carried out in the six largest cities in Finland: Espoo, Helsinki, Oulu, Tampere, Turku, and Vantaa. The study portrays a contradiction between the realized 3D city modeling projects and the expectations towards them: models do not appear to reach the broad applicability envisioned. In order to deal with contradiction and to support the development of future 3D city models, characteristics of different operational cultures in 3D city modeling are presented, and a concept for harmonizing the 3D city modeling is suggested.

The central outcome of the study is to understand the link between technical solutions and characteristics of different operational cultures. As we apply the characteristics of 3D GIS, BIM and computer graphics cultures in the development of 3D city models, we are able to underline why the different traditions of 3D city modeling cannot easily achieve an integrated solution for the stakeholders. Finally, a concept for a harmonized 3D city model can advance the development of a desired, multi-purpose solution.

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