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Potential of 3D city models for planning activities: application in a Swedish municipality

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Abstract

Nowadays, the use of geo-data 3D city models is rapidly growing in a variety of research fields since for a city administration being equipped of spatial data is an advantage for a large spectrum of application, such as urban and environmental planning, disaster monitoring and management and many others. Furthermore, there are many datasets and methods currently available that can be employed to generate 3D city models, which in turns can be used in various applications within the field of visualization. For this reasons, 3D city models currently represent effective support tools used in a variety of purposes including analysis, cities development, citizens communication and engagement and hence, also as a support throughout the decisional process. In the light of that, the aim of this thesis is, firstly, to provide a general overview about the current numerous fields of application of the 3D city models, which, as it will shown, are not only limited to visualization field. Successively, the generation process of a 3D buildings model has been detailed analyzed within all its phases, structured in: data acquisition methods, various types and data formats commonly used, data processing with the employment of different software currently available in the market and visualizations of the 3D city models in several applications. Lastly, an example of implementation, generating a 3D building model for the municipality of Vaxholm, Sweden, has been featured in this thesis. Pro and cons of the results achieved have been described, on the one hand, providing a practical demonstration of an hypothetical procedure that might be used to build a 3D city model within a certain set of data formats, and on the other hand, forecasting likely improvements and future applications to which the 3D building model generated might be extended.

Sommario

L'utilizzo di modelli tridimensionali di città contenti dati geografici, oggigiorno sta rapidamente crescendo in una varietà di campi di ricerca, poiché per un'amministrazione cittadina essere dotati di dati spaziali di un certo tipo è vantaggioso per un ampio spettro di applicazioni, come la pianificazione urbana ed ambientale, il monitoraggio e gestione delle calamità e in molti altri campi. Inoltre, diversi metodi di realizzazione e *data sets* sono attualmente disponibili e vengono comunemente impiegati nella generazione di modelli 3D per le città e che a loro volta possono essere utilizzati in varie applicazioni nel campo della visualizzazione. Per questo motivo, i modelli di 3D di città sono oggi considerati efficaci strumenti di supporto utilizzati per diverse finalità tra cui analisi, sviluppo delle città,

comunicazione e coinvolgimento dei cittadini e, di conseguenza, anche come supporto nel processo decisionale. Alla luce di ciò, l'obiettivo di questa tesi è, in primo luogo, fornire una panoramica generale sui numerosi campi di applicazione dei modelli 3D di città, che come sarà mostrato, non si limitano solo al campo di visualizzazione. Successivamente, è stato dettagliatamente analizzato il processo di generazione di un modello 3D di edifici in ogni sua fase, strutturandolo in: metodi di acquisizione dati, i vari formati e tipologie dati comunemente utilizzati, elaborazione dei dati con l'impiego di diversi software attualmente disponibili sul mercato, e visualizzazioni dei modelli tridimensionali di città in diverse applicazioni. Infine, in questa tesi è stato presentato un esempio di implementazione, in cui un modello tridimensionale di edifici è stato creato per il comune di Vaxholm, in Svezia. I pro e contro in merito ai risultati raggiunti sono stati descritti, da un lato fornendo una dimostrazione pratica di un'ipotetica procedura che può essere utilizzata per costruire un modello 3D per le città considerando un certo insieme di dati con formati diversi, dall'altro prevedendo possibili miglioramenti e future applicazioni cui il modello 3D generato potrebbe essere esteso.

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List of Abbreviations

ALS – Airborne Laser Scanning

BIM – Building Information Modeling

CAD – Computer-aided Design

COLLADA - COLLAborative Design Activity

DEM – Digital Elevation Model

DIM – Digital Image Matching

DSM – Digital Surface Model

DTM – Digital Terrain Model

ECW - Enhanced Compression Wavelet

FME - Feature Manipulation Engine

GE – Google Earth

GIS – Geographic Information System

GML – Geography Markup Language

GPS – Global Positioning System

INS – Inertial Navigation System

KML – Keyhole Markup Language

KMZ – Keyhole Markup Language Zipped

LIDAR – Light Detection and Ranging

LoD – Level of Detail

LoS – Line of Sight

LPS – Leica Photogrammetry Suite

OGC – Open Geospatial Consortium

POC – Piano Operativo Comunale

PSC – Piano Strutturale Comunale

RUE – Regolamento Urbanistico Edilizio

SME – Small and Medium-Sized Enterprise

SVF – Sky View Factor

TLS – Terrestrial Laser Scanning

UAV - Unmanned Aerial Vehicle

URL - Uniform Resource Locator

VRML – Virtual Reality Markup Language

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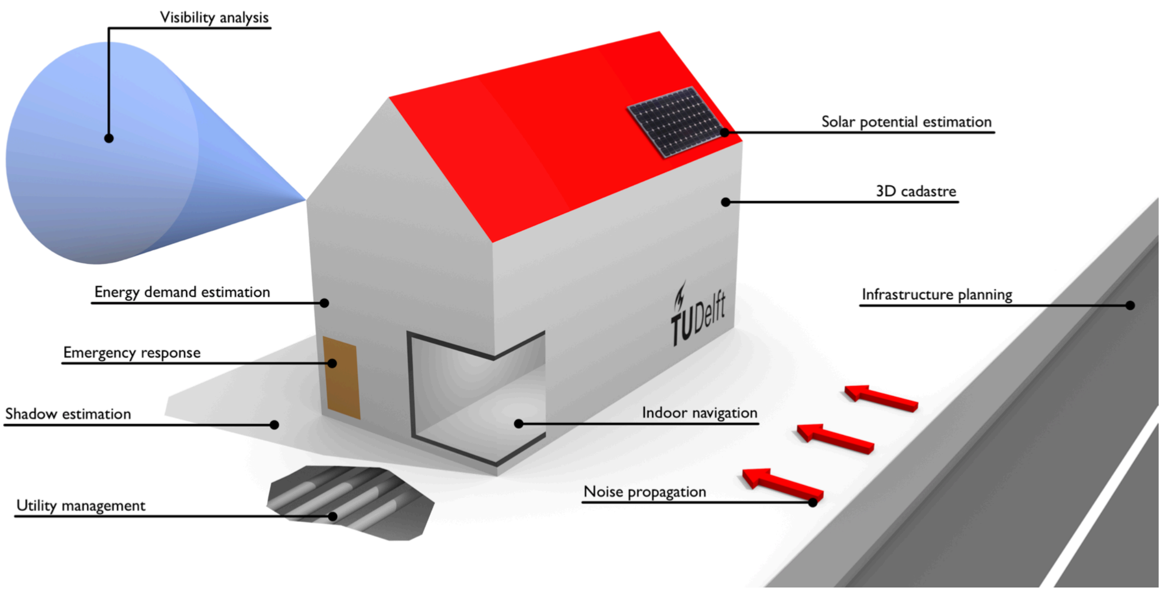
Introduction

During the last few years, digital 3D city models have achieved a high presence as valuable planning tools in a large number of municipalities and firms spread all over the world. Initially, the early use of 3D city models has been dominated by visualization only; the main purpose was providing public access to users for an attractive visualization of the urban environment and all its geographic elements in a certain area, taking advantage of 3D models for tourism and marketing purposes. In recent times, by virtue of new software and new modeling technologies, 3D spatial and non-spatial information has been implemented in several cities and, consequently, 3D city models have become estimable for various domains beyond visualization and have been extended to larger number of tasks, such as urban planning, disaster simulation, virtual-heritage conservation and many others. However, on the one hand, the increasing number of different applications that employ 3D city models, where each of them requires its own specific 3D data, and on the other hand, the complexity of 3D model generation process, have lead to a fuzzy vision about the real possibilities of utilization that 3D city models have.

In the light of that, aiming to put things right about these blurry topics, in the first section a comprehensive inventory of use cases has been provided, as it is shown in the figure below, which classifies the 3D data requirements to specific applications and clarifies which types of 3D models with their specifics features fit-for-purpose.



3D city models applied in a large number of application domains for environmental simulations and decision support (Biljecki *et al.* 2015a). Figure 3 in the text.

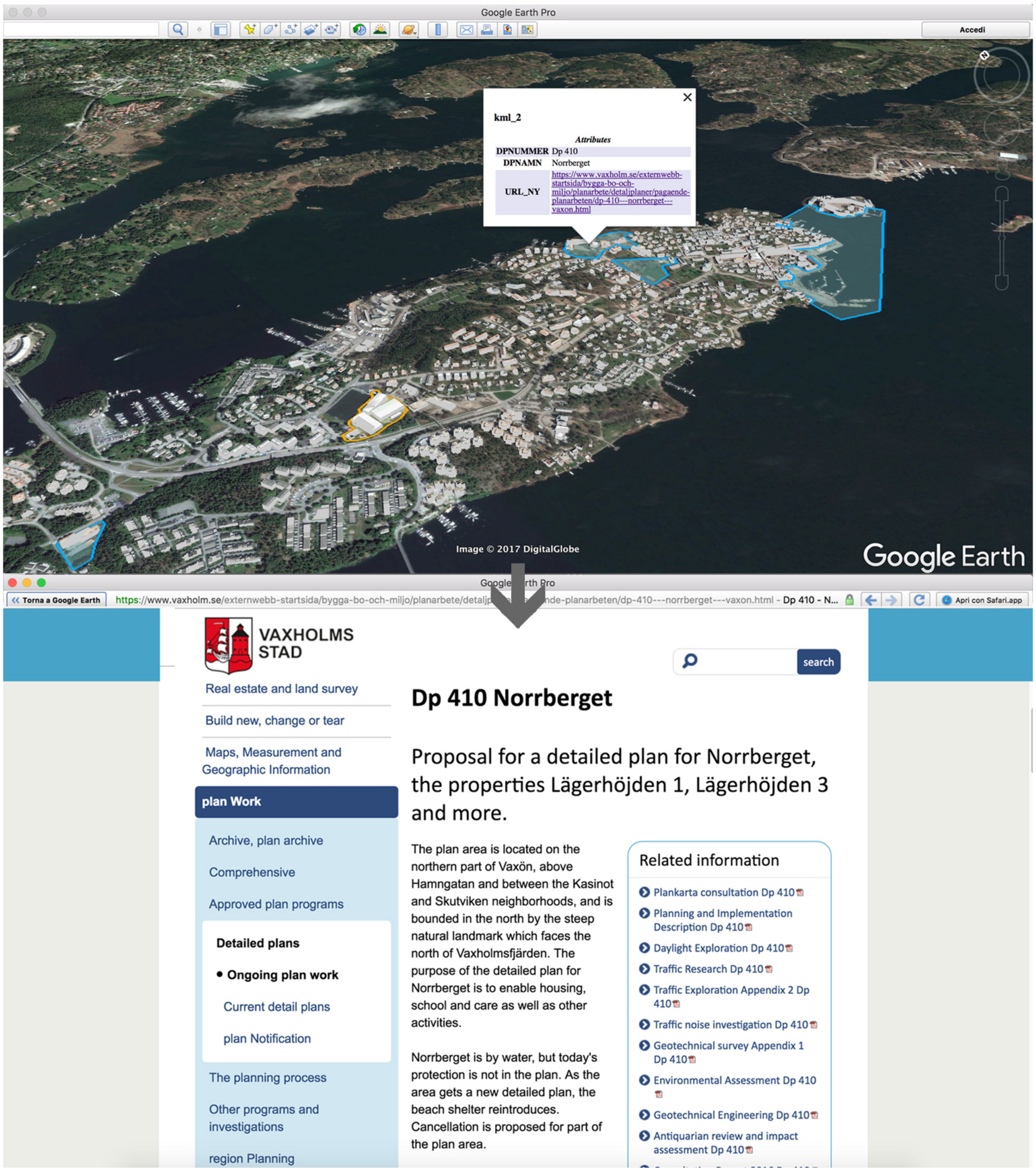
Since visualization seems to be the only criterion that is suitable and can cover almost all categories of applications, a wide range of use cases that employ 3D city models has been chosen and categorized into two groups. The first regards non-visualization use cases, where the visualization of 3D city models is not required since the results of the spatial operations can be just stored in a database. For instance, some domains part of this group are, the evaluation of solar irradiation, the energy demand estimation and the classification of building types for taxation. The second group concerns visualization-based use cases, where the visualization of 3D city model is essential and without it the use cases part of this group would not make much sense. For example, some use cases are: geo-visualization, visibility analysis, estimation of shadow, evaluation of noise propagation, estimation of population in an area, and many others. Successively, we have focused more on the use of 3D models as tools within the planning process. Indeed, 3D city models are commonly used to display virtually existing cities as well as to provide urban information to citizens about hypothetical new developments in a 3D environment. Additionally, thanks to today's web technologies, 3D city models enables local governments to publicly divulge to their citizens a three-dimensional visualization of plans and projects including their process of approval, but also it can be used in two-way communication where citizens can comment back and propose better alternatives after having inspected the plan, providing either positive or negative feedbacks to local authorities.

Furthermore, to better understand how much the opinion of diverse actors deserves attention throughout the whole process, two different approaches widespread among municipalities have been described, which use virtual city modeling to make engagement of different stakeholders faster and easier during the decisions-making process. The first is the user-oriented approach, which collecting citizens problems and needs, tries to figure out what the optimal alternatives that solve citizen's issues might be. The second is the e-participation, based on web technologies, that facilitates the communication of citizen's feedbacks about development plans promoted by authorities and eliminates the need to gather together in a certain place and in a specific moment since they can take part to the decision-making process just using a web portal. Lately, in this section have been underlined the reasons why cities should extend their 2D GIS implementations to the third dimension, identifying the additional insights that a 3D city model offers rather than a traditional 2D product.

In the light of the fuzzy vision previously underlined, in the second section the whole generation process of a 3D building model has been analyzed in detailed, going through all the essential steps that have to be done to create a 3D city model. Firstly, the current most used techniques to acquire data, employed in 3D city modeling, have been categorized into, photogrammetry and laser scanning based methods and also, have been identified which kinds of data can be acquired by each of them. After that, strengths and weaknesses for both techniques have been delineated. Later on, the data processing methods recently developed to reconstruct building models has been differentiated into, manual, semi-automatic and automatic methods, where the pros and cons for each of them have been analyzed. Successively, since 3D city model generation process consists of combining together different information, where each of them has different formats and characteristics, some data formats commonly employed by city administrations or firms to shape 3D city models have been presented, such as LIDAR point clouds and aerial oblique images, in order to define in detailed their features and provide some cases of studies where they have been used. The third step of 3D models generation process that has been described, concerns the choice of the right software to combine different data together and reconstruct a 3D city model. Indeed, which technique is used to create a 3D city model may depend on the application and on the level of details (LoD) of the resulting model. At present, there are various software available in the market for 3D city model generation, which can be based on BIM (Building Information Modeling) as Autodesk Revit, on photogrammetry principles as ContextCapture, Pix4D or Leica Photogrammetry Suite (LPS), or on data managing, as ESRI CityEngine and FME. For each of the formers the main features and functions have been delineated.

Subsequently, in the 3D modeling process, after having chosen the most feasible software to accomplish the results predefined, the data acquired are combined together and through this software the 3D city model is generated within all its details. Lately, the 3D model is visualized by an application platform. To accomplish the last phase of 3D city model generation process, the main goal is, firstly, considering the wide range of 3D visualization techniques available, and then choosing among them, which one is the most feasible for the set of heterogeneous data that have to be visualized together in the same 3D city model, in order to perform a given purpose in a certain context. Therefore, in this section has been underlined that the selection of an effective visualization technique for a 3D city model is important for the choice of the right platform to view abstract information of a 3D city model, and on the other hand, it is a difficult task due to the large number of criteria that have to be considered in advance. An example of an internationally widespread web platform, Agency9 CityPlanner, has been provided and also it has been properly described later on during the third section of this dissertation, introducing several cases of study where it has been employed.

The third section regards the description of a project developed during an academic internship attended in 2017 at Vaxholms Stad, the headquarters of the same municipality, situated in the Stockholm County, Sweden. The project aimed to create a system that allows 3D visualizations of Vaxön's urban structure, the area of study chosen since the most populated island of the whole municipality. By virtue of the software FME, and the combination of LIDAR point clouds, 2D footprints in shapefiles and ortho images, a geo database has been created to represent and manage a virtual LoD2 3D buildings model of Vaxholm. Lately, the content of the database has been transformed in KML, the format supported by Google Earth, to allow citizens to easily read and view the 3D model in a free- web-based mapping



On the top**:** the pop-up window cointaining a URL link (Own elaboration from GE), which connects directy to the Detailed plan information on the municipality's website (On the bottom). Figure 46 in the text platform as Google Earth. Additionally, Detailed plans and Projects planned for Vaxholm, with still an ongoing plan work, have been added to the 3D models. Indeed, as it is shown in the last page, in Google Earth these plans present a URL link that from a pop-up window connects them directly to the plan's information published on Vaxholm municipality's webpage. In this way, citizens had the possibility not only to inspect the 3D city model of Vaxön on GE but also to have access directly from the model on the interested area and to all the detailed information about a certain plan/project including their current *iter* of approval. Therefore, thanks to Google Earth functions, citizens can leave a feedback by e-mail to the city administration, claiming for their needs about a specific plan or just providing their points of view about what has been mapped on the 3D model. Lastly, based on the results achieved, likely improvements about the procedure employed have been forecasted and also additional applications to which the 3D building model generated might be extended in the future.

Methodology and organization

The objective of this dissertation is to investigate what the real potential of 3D city models can be for planning activities as well as for many others domains related to the city's development, in order to identify which procedure to create 3D city models can be considered as the most efficient for municipalities, and which advantages they can get if equipped with this planning tool. To gather such information, the main methodology used in this essay has been based on a survey and literature review of, mostly, online resources publicized in the last two decades, such as scientific journals, academic articles, thesis and project reports. These documents were related in some cases, to the current application and utilization of 3D city models in diverse domains and in others, to the broad number of different approaches used today to create 3D city models at various levels of details. Most of the literature found about the topic debated was in English; hence, this was the reason why the dissertation has been written in the same language. Also, about the cases of study taken as examples, in which cities were already equipped with 3D city models, they were mainly chosen in Europe, starting from Italy, Austria, Belgium, UK until Sweden where I have attended my internship and developed a 3D city model of Vaxholm. This study area has been selected because presents a mixture of historic and modern buildings with homogeneous architecture styles, which has made easier the reconstruction of the 3D buildings, and where the highest building was about 20 m.

Once all the documents have been retrieved, a comprehensive and systematic synthesis has been delineated through the sections of this essay, aiming to sort out the objectives aforementioned. First, it has been reported an overview about which application fields the use of 3D city models could be convenient for. Then, it has been provided an introduction about the techniques, currently available in the market, employed in data acquisition, processing and visualization, including international explanatory cases of study for each method described. Lastly, it has been proposed a hypothetical procedure, already implemented in Sweden, to create a 3D city model, which in turns will be used as tool for citizens engagement throughout the decision-making process.

Chapter 1

3D modeling overview

1.1 Geometrics and semantic properties of 3D city models

3D city models are digital representations of the urban environment, which include earth surface, vegetation, infrastructures, landscape elements and many others objects, where buildings are considered the most prominent features (Stadler & Kolbe, 2007). To understand carefully the meaning, each term of the definition has been separately defined:

- **3D**: indicates three-dimensional GIS (Geographic Information System) data, where each dimension is geometrically defined;
- **City**: denotes coverage in urban as well as rural areas, *e.g.* 3D topography. However, even though the term 3D city modeling is suitable for both contexts, most of the data available and the widespread applications are cities related;
- **Model:** implies a virtual representation of a certain object created through a modeling process. A model can be rendered on a 2D computer screen, or being physically printed (Biljecki, 2013).

Besides geometry, an important component of 3D city models is semantic information, which can be described as any information that is not visible as the geometry is, *e.g.*, the use of a certain building. Both geometric and semantic properties of 3D models are stored in several 'levels-of-detail' (LoD). The LoD approach is a coherent modeling of geometric and topological properties at each level, where geometric objects get assigned to semantic objects. The LoD definition is mainly used for the details of the buildings since buildings are the most important items in a 3D city model. This concept is quite significant in 3D city modeling since it defines the degree of abstraction of real-world's elements (Biljecki, 2013). Today, the number of cities that are representing their 3D city models according to the

CityGML[1] standard is growing. This standard has been issued by the OGC (Open Geospatial Consortium) to further decompose articulated objects. The CityGML standard defines five levels of details, as it is shown below in figure 1. LoD0 is essentially a 2.5D Digital Terrain Model (DTM). Buildings are represented in LoD0 by footprints or roof edge polygons (2D shapes in 3D space). Thus, this level of detail does not contain volumes or 3D objects and it is usually used for regional and landscape applications (Biljecki, 2013).

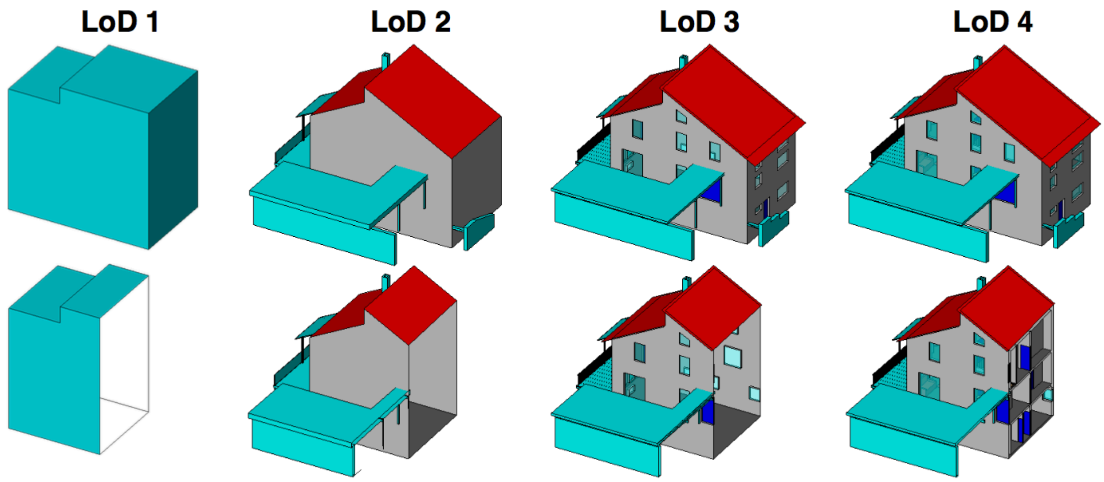


Figure 1. Four LoDs of CityGML. LoD0 is not shown here. Courtesy of Karlsruhe Institute of Technology (Biljecki, 2013).

LoD1 includes blocks model with prismatic buildings with flat roofs. This level is mostly used for city and region coverage.

LoD2 contains buildings with differentiated roof structures and thematically differentiated boundary surface. This level is more suitable for city districts and projects.

LoD3 presents architectural models with detailed wall and roof structures, possibly comprising doors and windows. It is frequently used for landmarks.

LoD4 completes LoD3 adding interior detailed elements in buildings, such as walls, façades, roofs structures, balconies, rooms, stairs, furniture, as well as several elements located outside,

[1] City GML: "is a common information model and XML-based encoding for the representation, storage, and exchange of digital 3D city and landscape models. CityGML provides a standard model and mechanism for describing 3D objects with respect to their geometry, topology, semantics and appearance, and defines five different levels of detail. Included are also generalisation hierarchies between thematic classes, aggregations, relations between objects, and spatial properties". (Biljecki, 2013).

like vegetation and transportation objects. Therefore, the relations between LoDs can be seen in the following picture (Biljecki, 2013). Below in figure 2 follows a LoD's schema.

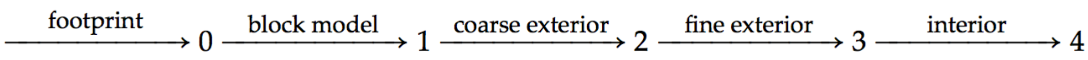


Figure 2. LoDs' schema (Biljecki, 2013).

Given these definitions, it can be argued that LoD0 cannot be considered a 3D city model since it is only a boundary representation in two-dimensions with heights as attributes. Besides further improvements in the exterior, LoD3 is essentially a LoD2 with windows and doors and a LoD4 is an upgraded LoD3 with interiors since external geometries and semantics remain the same (Biljecki, 2013). However, CityGML does not indicate methods for the automatic derivation of the different LoDs, and relationships between different LoDs are not maintained (Fan & Meng, 2012).

On the one hand, contemporary methodologies seem being limited to reconstructing 3D city models with a LoD2, which includes only external surface of a building, such as walls and roofs, and on the other hand, nowadays, users are becoming more interested in querying, for instance, a room's specific measure of a public building, hence, they need more geometrically and spatially accurate building models with higher level-of-details (LoD3 or LoD4). For example, the level-of-details has to take care of the intended scope of use of 3D geo-information, because some use cases require datasets of a certain minimum of LoD to be usable (Biljecki *et al.* 2015a). Therefore, a detailed 3D city model provides a more realistic geographical representation of an entire urban area as well as enables users to retrieve specific object information when they want to interact with the model. Nevertheless, producing such detailed 3D models is a long and difficult process, due to the time consuming, data collection and manual model processing, in which a lot of spatial and non-spatial information is gathered and linked to complete an object's description. Therefore, providing these kinds of models still, it might be considered as a big challenge (Truong-Hong *et al.* 2013).

Despite their complexity, 3D city models have achieved a high presence during the past years. A current trend shows that cities need to extend their 2D GIS implementations to the third dimension. A large number of cities, mainly municipalities with high population density, have already implemented tridimensional models, which provide attractive visualizations of their urban structure as well as visibility for marketing and tourism purposes.

1.2 *Applications in several fields*

Spatial data, according to contemporary perspectives, are considered essential for a large range of applications, such as environmental planning and monitoring, security, disaster management, risk assessment, location-based services and other purposes. Nowadays, the development of new technologies has allowed the implementation of 3D geo-information data in several cities, which is rapidly growing and expanding in different research fields. The main reason, as aforementioned, is that these kinds of applications provide public access to explore 3D geographic elements, *e.g.,* roads, buildings, and other environment infrastructures built in a specific context (Truong-Hong *et al.,* 2013).

The early use of 3D city models has been dominated by visualization only. However, by virtue of new software and new modeling methodologies, 3D city models have become valuable for several domains beyond visualization, and are currently used in a large number of purposes as it is shown below in figure 3.

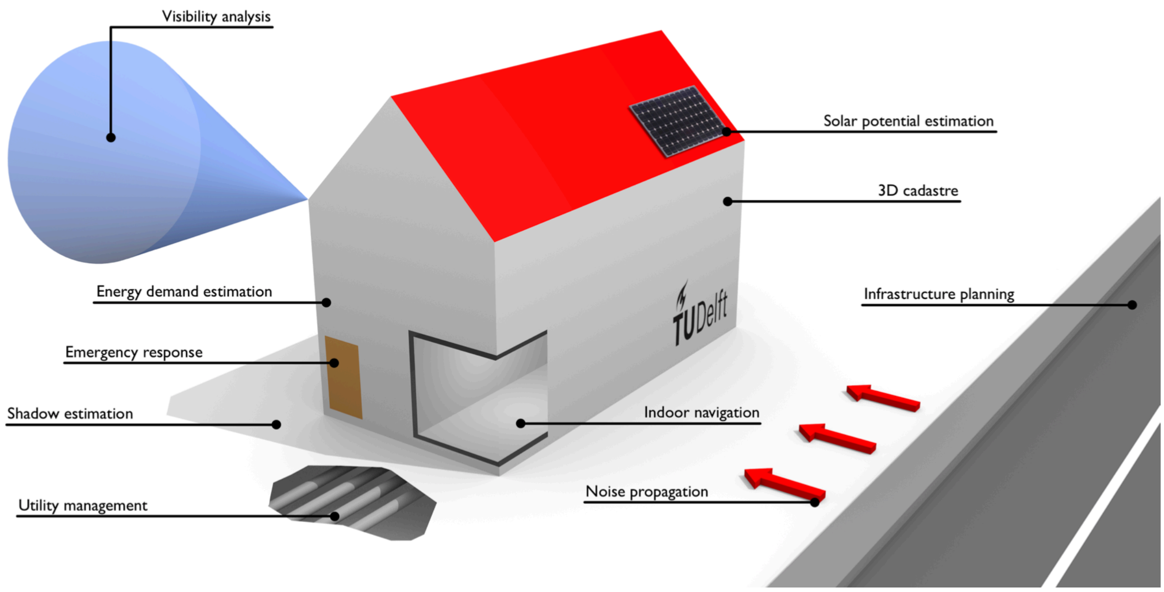


Figure 3. 3D city models applied to a large number of application domains for environmental simulations and decision support (Biljecki *et al.* 2015a).

During the past years, some researchers have studied the applicability of 3D geo-information, focusing on solving industrial and experimentation problems. A 2000 research, Batty *et al.*, promoted a conceptual study about the use of 3D city models. They have segmented the use of three-dimensional models in several categories: emergency services, urban planning, telecommunications, architecture, facilities, marketing and economic development, tourism and entertainment, environment, education, and other fields. Ross in 2010, after a research about the same topic, proposed a general taxonomy of 3D use cases, which relies on the type of data that each model contains:

1. Applications based on geometry (estimation of the shadow).
2. Applications based on geometry and semantic information (estimation of the solar potential).
3. Applications based on domain specific extensions and external data (noise emission calculation).

However, even though this approach provides a clear classification of use cases, is important underlying that the categories are not 'exclusive' in all cases, but some applications might fit in more than one category. For example, to estimate the propagation of noise in an urban environment, only the geometry of buildings is needed. Furthermore, if hypothetically semantic information of geometries is also known, such as inhabitants or building's material, these data may represent important improvements for predictions and better assessment of noise consequences (Biljecki *et al.*, 2015a).

Since visualization is the only criterion that is suitable and can cover almost all categories of applications, the taxonomy of use cases that was mentioned above, can be further categorized into two groups:

1. **Non-visualization use cases**: visualization of the 3D model and the results of the 3D spatial operations are not required. The results can be visualized but it is not essential to achieve the task of the use case, but rather can be stored in a database, *e.g.* solar potential of a roof surface.
2. **Visualization-based use cases**: Applications where visualization is essential and the use cases would not make much sense without it; for instance, navigation, gaming, and urban planning.

Based on these two groups above mentioned, distinct use cases have been identified in several application domains (Biljecki *et al.,* 2015a).

1.2.1 Non-visualization use cases

Estimation of solar irradiation

This analysis is, arguably, one of the most prominent use cases in 3D city modeling (Biljecki *et al.* 2015b). 3D data, *e.g.* both city models and laser point clouds, are used to evaluate the solar potential on rooftops in urban areas, for example, to assess how much a building is exposed to the sunlight in order to evaluate the suitability of a roof surface for installing photovoltaic panels above it. Moreover, three-dimension models provide geometric information such as orientation, the area of the roof, the tilt, which is used as input for the solar empirical models. Another estimation derivable from this application, even if less prominent, can be the evaluation of the thermal comfort, *e.g.* the detection of buildings that are exposed to a big amount of sunlight (Biljecki *et al.*, 2015a).

Energy demand estimation

The energy demand of households demonstrates the value of semantic 3D city models. Researchers have used 3D city models to combine the data of the building's volume, number of floors, type of buildings, and other features to predict the energy demand for heating or cooling (Kaden & Kolbe, 2014). Below in figure 4 follows an example of heat demand.

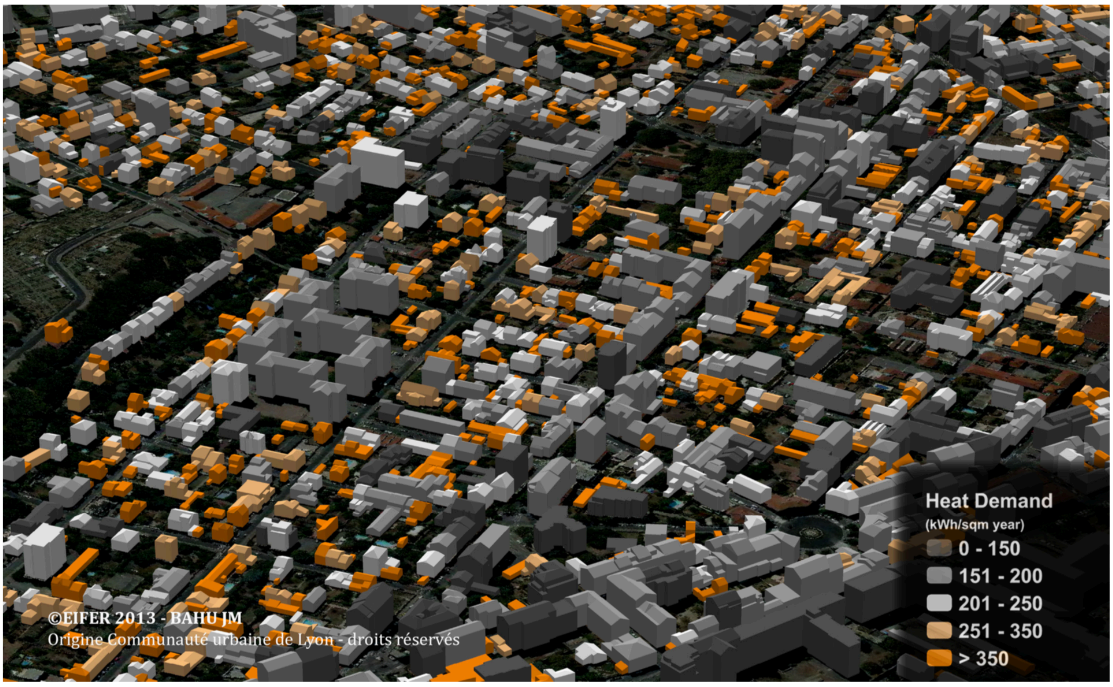


Figure 4. Results in the estimation of the heat demand of buildings (Bahu *et al.* 2013).

For instance, the estimation of the energy demand is significant to assess the benefit of energy-efficient retrofitting. Previtali *et al.* in 2014, analyzed the use of 3D city models to evaluate the cost of retrofitting of a building. Furthermore, related retrofit planning analyses have used materials information, data and renewable energy resources.

Classifying building types

The 3D geometry of volumes is used to detect the type of a building, *e.g.* shape of apartments and detached houses. This classification has different applications in various domains. For instance, the distribution and shape of a building type in a neighborhood may help marketing and real estate management, hence, it may, consequently, give some clues about its potential for taxation and valuation of buildings. Furthermore, as mentioned before, the type of a building is an important data that, combined with other features, can predict the energy demand for heating or cooling (Biljecki *et al.,* 2015a).

1.2.2 Visualization-based use cases

Geo-visualization and visualization enhancement

Visualization is considered as one of the most used applications of 3D city models since is able to provide panoramic views, web visualizations, profiling and other related works. Furthermore, it is generally used to enhance the presentation of results from such analyses, which can be related to GIS, such as in a visibility analysis, or which are not necessarily related to GIS, such as economic activities (Biljecki *et al.* 2015a).

Visibility Analysis

3D city models are fundamental for various kinds of visibility analyses. For example, determining the line of sight (LoS) between two points in an urban environment and also evaluating the volume of sight. Moreover, based on the assumption that the view from an apartment may have influence on its price, further examples might be: the estimation of a landmark visibility, which considers the façade visibility in a city marketing perspective, in order to improve the road safety; and the estimation of the sky view factor (SVF), *i.g.,* how much the sky is obscured by surrounding buildings, which can be used for urban climate studies, and thermal comfort analysis (Johnson & Watson, 1984).

Estimation of shadow

The estimation of shadow created by buildings is generally used in urban planning field to evaluate, for example, the impact that a new building has on its surrounding area. Indeed, such kinds of analyses are frequently required by municipalities since they are used to assess future projects. This use case can also be combined with estimations previously mentioned, such as evaluation of the solar potential of buildings because it might affect negatively the yield of a photovoltaic solar panel, and estimation of the thermal comfort buildings (Biljecki *et al.* 2015a).

Estimation of noise propagation

For this use case, 3D data is used to create models that say how many urban citizens are damaged by noise pollution, and how they can mitigate it, for instance, locating noise barriers (Ranjbar *et al.*, 2012). This estimation started being more relevant in Europe after the implementation of the Environmental Noise Directive 2202/49/EC which demands European countries to be provided with strategic noise maps that inform the public about noise exposure and its effects (Czerwinski *et al.*, 2006). GIS applications are fundamental in noise mapping, but using 3D city models is possible to assess the propagation and impact of noise in the environment, which is significant, especially, in urban areas (Stoter *et al.*, 2008). In this application some details are more indispensable than others, such as the building's material, instead, others are totally irrelevant in the analysis, for instance, the textures. Mejers *et al.* in 2012 argued that noise modeling in 3D would benefit from having buildings with more details available only close to the source of the noise since the farther buildings have less influence on the propagation of noise. This is an interesting example of using mixed LoDs in the same 3D model.

3D Cadastre

3D city models have been used recently to manage and collect data about legal objects. For instance, in a visualization context, instead of an elementary 2D cadaster, which has some limitations, a property would be represented investigating its portrayal aspects in a 3D cadaster. For this reason, some governments have recently been focusing on developing property registration in three-dimensions to provide insights into complex property situations, such as vertical ownerships in buildings and subsurface constructions, *e.g.* cables and pipelines, parking garage (Billen & Zlatanova, 2003).

Visualisation for navigation

3D volumes are used to facilitate user's orientation for navigation purpose in an urban context. Indeed, navigating in an urban area through the use of 3D city models may help users to feel familiar in a certain setting. Additionally, the third dimension with semantic information provides further values, since the visualization can be enhanced improving its features (Nedkov, 2012).

Estimation of population in an area

The use of 3D geoinformation allows calculating the population of a specific area because the size of a building gives some clues about the number of residents. This estimation has become a relevant topic of several research papers, because the output can be used in various application domains, such as optimization of mobile radio signal coverage, *i.e.*, improvement of the network to cover more people, emergency response for evacuation, *e.g.* estimation of the affected population by a flooding (Kunze & Hecht, 2015).

In the light of the classification above mentioned, about contemporary applications of 3D city models, it is clear that they are currently used in a lot of domains for several purposes. The second group of use cases, related to visualization-based applications, is broader than the first one. This suggests that visualization is a fundamental feature of the contemporary workflows involving 3D city models. Thus, this analysis has revealed some interesting patterns, about the development and large utilization of 3D city models, and how a lot of use cases already prove the valuable role and their growth over time.

1.3 *A tool for urban planning and facility management*

At the present, urban 3D models are widely used by designer and urban planners as decision-making tools employed to explore, plan cities and especially actively act on them. Urban planning is a field with blurry boundaries and a broad variety of actors. 3D geo-information is a frequently used tool in this field for different tasks. For instance, a visualization application of 3D city models displays virtually existing cities as well as may provide urban information to citizens about hypothetical developments or traffic information in a 3D environment (Buhur *et al.,* 2009). Furthermore, today's web technologies and availability of 3D city models, at different levels of detail (LoDs), enables local governments to communicate spatial plans to their citizens, but also it can be used in two-way communication where citizens can comment back and propose better alternatives, submitting either positive or negative feedbacks to local authorities (Onyimbi *et al.,* 2017).

This means that 3D city models can be useful to investigate local dynamics and best fitting urban indicators for a future enhancement (Biljecki *et al.,* 2015a). Recently, 3D geoinformation models have been employed in several facilities administration, including a large number of urban objects, besides residential buildings. For example, managing harbors, airports, infrastructures and utility networks, which support both visualizations of different volumes in a certain area and semantic information about those facilities (Zlatanova & Beetz, 2012). Furthermore, 3D city models have been used in the field of disaster management, where they may have a double role. For instance, after a natural disaster has occurred, the 3D city model can be employed by emergency medical services or fire departments to manage local transportation infrastructure and locate equipment. Differently, they can be used when, for instance, an earthquake has significantly damaged a city, and the model can help to reconstruct the emergency areas, analyze the level of danger and assists as a basis for the rehabilitation of buildings.

However, today, for many municipalities virtual city modeling is mainly employed as a new method to manage city administration, since the inclusion of public participation during decision-making process may open different perspectives for future projects, and facilitate engagement of several stakeholders throughout the planning process. Every type of change, especially in an urban territory, has economic and social consequences. The implementation of a new development plan in a specific context affects lives of citizens who live or work close to the area covered by the plan. For instance, the enlargement of an existing road, on the one hand, will increase mobility, but on the other hand, will decrease the livability of residents who live in the proximity of that road (Onyimbi *et al.,* 2017). In the light of that, it can be asserted that inhabitants should have a voice in the design of urban plans, and more in general, throughout the whole planning process. Nowadays, there are several approaches widespread among municipalities that use virtual city modeling to make engagement of different stakeholders faster and easier during the decisions-making process. In the next paragraphs, two different examples of stakeholders involvement will be analyzed to better understand how much the opinion of various actors deserve attention throughout the whole process: a user-oriented case study in Salzburg and an e-participation technology in Kismu.

1.3.1 User-oriented

One likely method to achieve what mentioned previously might be a solution-oriented approach. This process starts with the collection of citizen's problems and needs, then understanding them completely and carefully, and lately, trying to figure out what the optimal solutions that solve citizen's issues might be. Therefore, user-oriented requirements may become helpful tools for a more transparent communication and a better decision-making process, which will improve the quality of the planning process.

An example of good practices of land planning has been executed in Salzburg, Austria. A study has been accomplished thanks to the research project *Digital Cities*[2]*,* which Autodesk has conducted with Z_GIS and the City of Salzburg, as a pilot city. The research was focused on the analysis of the impact of a future urban development in Salzburg. To do that, a combination of city data with realistic visualizations and simulation tools, allowed Salzburg authorities to view and interact with the city landscape and analyze the impact of future urban planning, tourism, and economic development projects before they are built (Autodesk, 2008). Lately, as aforementioned, aiming to accomplish an integrated tool for the working processes, a user-oriented approach was implemented. Initially, workshops with the city departments of urban planning and facility management were organized, aiming to gather information about tasks in contemporary workflows and about the support that a digital city may offer to them.

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[2] *Digital Cities:* "The Digital City initiative is Autodesk's unique technology designed to provide a collaborative environment for visualizing, analyzing and simulating the future impact of urban design and development at a city-wide scale". http://www.autodesk.com/digitalcities.

The workflows were mainly related to urban planning and facility managing. Subsequently, the data gathered has been evaluated and divided into specific requirements for a digital city. The users could express their needs that, in a second moment, have been structured in detailed requirements for digital cities. These requirements covered all the components of the digital cities working environment and aimed to embrace all the tasks that had value for the city of Salzburg (Albrecht & Moser, 2008). Thus, this kind of analysis in order to be user-oriented might be considered context-oriented as well. Each task has been described and assigned to a field of expertise, mostly connected to the field of planning and facility management. However, the survey and the workshops have helped to find additional requirements and identifying new tasks. After these considerations, two application areas have been selected: the first area concerns visual communication of planned development, considered at a different scale, from building modifications to planning the whole city districts and employing the perspective view on the proposed development via visualizations and navigation in the city model. This also represents the communication basis that involves stakeholders of different areas of expertise. The second application area regards the management of geographic objects that need to be represented in three-dimensions and that are spread over a big area of the city. In both application areas, respectively planned modifications and geographic objects were integrated into their surroundings and might be analyzed by their spatial relations with other geographic elements (Albrecht & Moser, 2008).

In the light of that, it can be argued that the *digital cities* environment may help cities like Salzburg to visualize and communicate prosed changes in urban areas to inhabitants. The data collected, especially about urban planning tasks, can be suitable for other urban contexts, such as cities with equal size, the number of inhabitants, levels of development, social environment, and historical buildings structure.

1.3.2 E-participation

Web technologies, today, help to facilitate the communication of citizen's feedbacks about development plans promoted by authorities in order to eliminate the need for citizens to gather together in a certain place and in a specific moment. Through these technologies, a citizen may choose how, when and where take part, even anonymously if he wants, to the decision-making process. Moreover, 3D visualizations of 3D city models encourage the exchange of different alternatives among stakeholders. During the past years, e-participation has been frequently used to involve citizens in urban planning and management, but its use is still moderate in developing countries (Onyimbi *et al.*, 2017).

Aiming to prove the feasibility of the e-participation approach in developing countries, a 3D model with a web portal access has been created for the city of Kismu, in Kenya. Experiments have been held to measure the ability of six groups from different backgrounds. The 3D model created was visualized in a web portal, provided by ArcGIS Online, and tested to verify the suitability for e-participation. Each participant had the possibility to take part remotely, removing the need for meetings throughout the whole process. Essentially, each citizen could easily create an account, log in, view, navigate through and leave either positive or negative comment in the portal. Subsequently, opinions, proposals and various alternatives gathered have been discussed throughout plenary workshops (Onyimbi *et al.,* 2017).

To verify participants abilities coping with the designed 3D model, two tasks have been identified: the first regards 2D maps on A3 sheets that show plot numbers with road networks and a list of feature names. Each participant had to pick the name of a feature in the list, locate it and mark it in the 2D map within a time limit. The second task has the same process, but with a 3D city model stored in a web-based portal. The participants' performance has been measured in terms of efficiency, *i.g.*, calculating the time needed to complete the tasks, effectiveness, *i.g.,* counting the number of correct objects identified, and satisfaction, *i.g.,* analyzing participant reflections on their experiences (Onyimbi *et al.* 2017). For all groups, the second task (3D model) has taken less time than the first one. However, the experience had an influence on it, indeed, planners needed less time on average, on the other hand, students needed most time for both tasks. At the end, the 3D task appeared in more correct answers than the 2D task, but none of the groups were able to provide all the correct answers within the time span (Onyimbi *et al.* 2017). The results have shown that the web-based geoportal has to be improved since the participants' abilities were affected by some imperfections in the interaction with it.

Given that, it can be argued that mobile phones have a high diffusion rate among the population, thus e-participation using different web-technologies may become one of the best approaches recently used. Participation of some actors does not have to necessarily become part of all major decisions. However, a fundamental step, significant to stimulate public participation, is to identify issues and critical questions where citizen's opinions are needed, and also clarify participant level of influence. Furthermore, the addition of interactive facilities could make the 3D web portal more flexible and easier to use, enabling exchange information and learning since the way users experience an e-participation tool depends on its complexity, design, purpose, and above all, on its context (Onyimbi *et al.,* 2017).

The inclusion of different approaches, related to the engagement of various stakeholders with different roles and power of decision throughout planning process, and the extension of the study area, including every urban element and activity located in the environment, allow cities to move from isolated tasks limited to individual departments to an integrated tool for urban planning and managing (Albrecht & Moser, 2008). Hence, integrated 3D city models can support working processes and decision-making processes within communities.

1.4 *Why would municipalities be interested in the creation of 3D models rather than 2D maps?*

As it has been unerlined in the last paragraphs, a current trend shows that municipalities want to expand their 2D GIS implementations to the third dimension. Over time, theory, technology and decision methodologies have changed focus from a 2D system towards more elastic decision support role that includes 3D elements (Herbert & Chen, 2015). Indeed, 3D city models have been already generated for a broad number of cities, especially focusing on visualization-based applications oriented towards marketing and tourism purposes (Albrecht & Moser, 2008). In the light of the different applications of 3D city models previously analyzed, it can be asserted that 3D city models besides the broad usability in various fields, they offer additional insights rather than a traditional 2D product (Lemmens, 2017). For this reason in this research, only use cases that have a clear benefit from 3D geo-data have been included, such as applications which are only suitable for 3D city models and use cases which are feasible with 2D data but that are substantially enhanced when 3D data is used (Biljecki, 2015a). For instance, during the estimation process of solar irradiation, is not possible evaluating the yield of solar panels based on rooftops without a 3D city model

Figure 5: Noise pollution by a tram line, where the red, orange and green contours represent high, medium and low noise pollution respectively (Lemmens, 2017).

as well as estimating noise pollution is certainly more accurate when is executed on 3D models, rather than on 2D maps. One the one hand, 2D GIS is frequently used for this task, but on the other hand, a 3D geoinformation provides an advantage over it since, due to refraction, sound levels may largely change at different elevations of the same planar coordinates, as it is shown in figure 5 in the last page (Kubiak & Ławniczak, 2015). This happens because sound propagates through the air in all directions. Thus, noise levels differ not only based on distance from the source, but they are also based on the elevation, which cannot be shown when working in 2D. Another example regards routing, which is a typical 2D application but is increasing its importance in 3D city models context where it is used in particular outdoor navigation tasks which, instead, are problematic in two-dimensions. For instance, to investigate the optimal route in pedestrian paths, a 3D visualization allows identification of three-dimension elements such as ramps, stairs, and obstacles (Slingsby & Raper, 2008). Therefore, these kinds of specialized applications of 3D city models, which need pre-processing of data, are essential for municipalities since can enhance the tasks managing (Lemmens, 2017).

As aforementioned, 3D city models often make user's orientation easier in navigation tasks, since he can feel more familiar in certain settings. However, 3D visualizations can suffer from perceptual issues, such as occlusion and perspective changes, due to the scale that is not uniform over the view, and thus measuring the distances become troublesome. Indeed, 2D top views are significant for navigation purposes, as they supply overview information without occlusion and have also more regular scale that makes them better for distance estimation (Shepherd, 2008). In brief, on the one side, 3D representations are considered faster and more accurate than 2D representations for shape-understanding tasks, involving blocks and terrain, as well as for urban planning purposes, developing a sense of the larger context of a building in its environment. Instead, on the other side, it has been proved that users employ mostly 2D visualizations for navigation tasks rather than 3D ones because top view visualizations require less time to be understood and to follow easily a certain route. Thus, it can be assumed that multiple-linked views, made through a mix of 2D and 3D views, might be the most helpful for users needs (Bernasocchi, 2012). Nowadays, there are still some weaknesses in the employment of 3D city models. Many researchers argue that there is not such thing as general-purpose 3D city models, since they may provide generic datasets procured by cities and released as open data. Actually, this skill belongs to a 2D dataset, which can be collected once and used for many purposes. Instead, the same does not work for the third dimension. Requirements differ for every application and software; data formats are not always feasible, and there is often a lack of thematic completeness. Therefore, the creation of one dataset that is suitable for almost all applications is problematic, hence, there is still no one-size-fits-all 3D dataset, but only a dataset that can be suitable for some uses. For instance, a LoD2 3D city model has a dataset that might be used for solar potential estimations as well as in urban planning, however, it is unreal thinking that the same dataset would be feasible for a broad range of applications as in the case of a 2D GIS (Lemmens, 2017).

In conclusion, considering the limits that 3D city models still have in terms of interoperability, when municipalities or private firms design the technical requirements and, subsequently collect the data needed to achieve the goals fixed, they should focus only on a set of predetermined applications of 3D city models.

Chapter 2

3D city model generation

2.1 *Contemporary approaches to data acquisition and data processing*

The 3D city models generation is, quite often, a long and difficult process that implies various phases during which different datasets are integrated. Normally, a 3D model is made of different objects and is created by using data sets from several sources and with various file formats. Some examples may include GIS, CAD (Computer-aided Design) or BIM (Building Information Modeling) spatial data, but also non-spatial data as attributes. GIS data, such as base maps, DEM (Digital Elevation Model), DTM, land use maps, administrative boundary maps, road network data and many other files, are frequently required for any type of 3D city model. Also, CAD data have a fundamental role in 3D city models generation, indeed, buildings with the required level of details can be frequently used as CAD files and, combined with other data format, generate 3D models, otherwise, they might only be designed and edited in a CAD environment (SBL, 2016). Therefore, 3D city models consist of combining together different information, where each of them has different formats and thus, the crucial issue is to acquire, manage and combine these diverse materials into a virtual uniform representation of the environment. Hence, since 3D models are composed of different data sets, merging and adapting them to work all together can be considered as a big challenge.

The first factor to take into consideration during the first phase of 3D city modeling is to be provided with the right data to generate the model, and thus to acquired those data formats needed to do that. The raw data employed in 3D model generation are collected through several acquisition methods and then processed with a broad variety of software to shape the 3D city models. Data acquisition, essentially, consists of using the sensor data to determine geometric and semantic information of a certain imaged scene (Förstner, 1999). Thanks to recent developments in some geomatics techniques, such as photogrammetry, remote sensing, and laser scanning, building models can be semi-automatically or automatically reconstructed combining various resource materials, for instance, given the geometric resolution of satellite imagery and point clouds. To clearly identify what the range of contemporary techniques to acquire the data employed in 3D city modeling and, successively, to process those data, the most employed methods have been identified and categorized into two groups.

The first is based on data input techniques and includes photogrammetry and laser scanning based methods to acquire data; the second is based on automation and regards automatic, semi-automatic and manual methods to generate a 3D model (Pal Singh *et al.,* 2013). Additionally, the first geomatics techniques group has been further categorized in the following manner:

1. Photogrammetry based methods

- Aerial photogrammetry based methods
- Terrestrial photogrammetry based methods
- Satellite photogrammetry based methods
- Digital Image Matching

2. Laser Scanning based methods

- Aerial laser scanning based methods
- Terrestrial laser scanning based methods

Each of them is differently used according to diverse requirements and to which approach is applied (Tunc, n.d.).

2.1.1 Photogrammetry based methods

Photogrammetry is a remote sensing technique that, thanks to photographic images, inspects geometry properties of those objects that are visible in the image. The fundamental task is to determinate the geometric relationship between images and objects as they were in the capturing moment (Mikhail *et al.*, 2001). Also, photogrammetry based methods are used at different scales and positions to collect data and successively reconstruct 3D city models. The aerial photogrammetric method provides a more appropriate acquisition of 3D city models, compared to classic photogrammetric techniques. Indeed, the aerial imagery allows detecting the structure as well as the dimensions of a building, instead, classic photogrammetric measurements, which are point based, waste a lot of time to recover this information and are not able to capture the inherent structure. For these reasons, they cannot be considered convenient economically. Furthermore, aerial images are considered as one of the most used data, thanks to the high-definition that characterize them, *e.g.,* adequate level of details (at least a scale of 1:5.000) with forward and side overlaps of 30% and 60% respectively. These features make possible to recover a lot of buildings details, and also to have a maximum of 0,2 meter in height as the measurement error (Ulm, 2003).

Differently, in terrestrial photogrammetry, the camera used is located in a stationary position with an elevated level. Both aerial and terrestrial methods are used for mapping and measurement tasks but since the methods work differently they provide diverse results. The aerial photogrammetric is suitable when a broad piece of land has to be mapped, instead, the terrestrial method is preferred when planners want to monitor and map bridges, transport or pipelines network, hence analyze issues on a smaller piece of land. However, urban planning takes advantage of both methods aiming to evaluate, for instance, a new project for a certain area. Indeed, on the one hand, the aerial method gives a clear view of the proposed project with its surroundings; on the other hand, the terrestrial one shows interrelation between urban constructions, safety issues, disaster management and other obstacles. Therefore, the usage of both methods provides data sets that may generate an efficient plan for any kind of construction project (DIY, 2014).

Recently, high-resolution satellite images have been frequently employed for data acquisition of large areas. For these kinds of images, the capturing process of data is not really different from the aerial ones, but the results show some differences in terms of accuracy, which is less in a satellite image, and also in measurement error, which can be up to 1 m in height (Ulm, 2003).

An effective method for data acquisition through photogrammetry is Digital Image Matching (DIM). Indeed, the employment of DIM for automatic points transfer through photogrammetric applications is a widespread standard method. These kinds of software that integrates features or intensity based matching for automatic aerial triangulation are part of the photogrammetric world since two decades. However, by virtue of some enhancements, such as an optimal adaptation of algorithms for surface and object reconstruction, the technique has been sharpened to create photo meshes out of 3D point clouds. The images can be captured from either an aerial survey, *e.g.* drones, or ground-based static and mobile image capture, in which a wide variety of cameras types can be used, from a GoPro to a 'task-built' air survey camera system (Coumans, 2017).

In DIM the main quality regards the resolution which provides to imagery, in fact, DIM allows an easier production of 3D models through up to 300 gigapixels of photos, which have fine details, sharp edges and geometry accuracy. Any kind of digital camera can be employed, but certainly, cameras equipped with larger sensors and high-quality lengths can provide more accurate and a bigger amount of information, and consequently better results. Talking about the additional details that a DIM may provide, it can be assumed that the essential difference between traditional digital photogrammetry and DIM consists of their results. After a standard photogrammetry process, the result obtained is usually a 2D output, or sometimes, even a DSM. DIM, instead, adopts a combination of photogrammetry and computer vision building realistic 3D models in two formats, mesh or point clouds. Furthermore, there is also a big difference in terms of efficiency throughout the production process. As aforesaid, several zones of the scene can be acquired thanks to different types of cameras, which enable multi-resolutions of data. The advantage is essentially that, with a low resolution (5-10 cm), large areas can be captured, and then with a higher resolution (1mm-2cm), specific objects, such as buildings, facilities, and infrastructures, can be captured providing an amount of additional detailed, which using a traditional photogrammetry procedure could not be easily managed (Coumans, 2017).

Looking at some existing examples may help to understand why DIM is arguably considered attractive for municipalities. DIM provides new values opportunities in surveying and engineering, thanks to a continuous surveying throughout the lifecycle of infrastructures, where an image interpretation is essential, instead, laser scanning has limitations with a longer acquisition time and a less dense survey. The London Bridge Station project in the UK is a clear example of what said above. The plan included the reconstruction of its main promenade with fifteen new platforms and the installation of new retails stores and facilities. The group of engineers who led the project, the Costain Group, needed a meticulous 3D representation of the brickwork structure degradation, as it shown in the next page in figure 7, to understand the subsurface and, consequently, the reconstruction potential. Moreover, the 3D model had the aim to engage various stakeholders to make better decisions on a short schedule. Considering the age of the structure and also, the limitations that laser scanning has since it would cost too much and take too long to capture the area with one or perhaps two scanners, the engineers have chosen to experiment DIM for the initial survey and the regular updates. Thanks to the speed and the small size of a digital camera to capture the old surface area, a denser survey (than a scanner would) has been delivered and provided color, brought less disruption for the on-site workers and enabled designers to briefly identify the bricks from the mortar joints (Coumans, 2017).

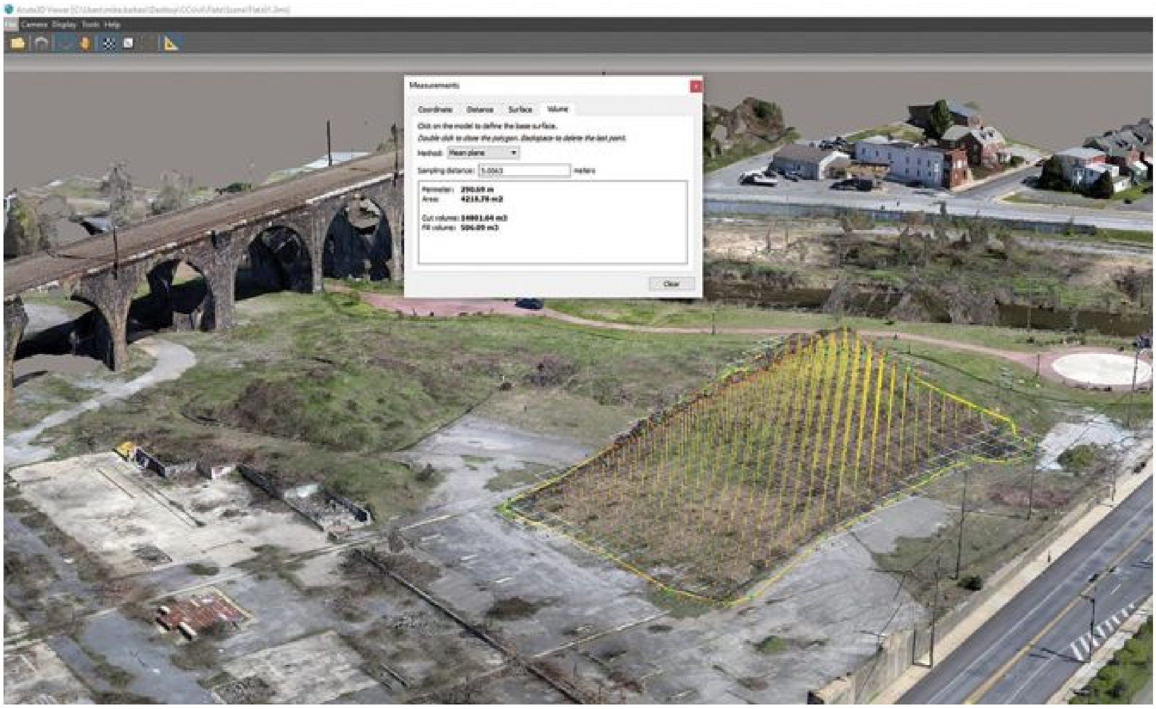

Figure 6: DIM employed for the representation of the brickwork structure degradation in London Bridge Station

In virtue of that, they themselves, but even an hypothetic client might use DIM (joined with *ContextCapture,* a Bentley product), to treat the images, converted into 3D mesh models, in order to make the decision-making process easier, furnishing clear documentation of existing conditions that might be used throughout the lifecycle of the infrastructure (Coumans, 2017). Therefore, DIM technology can reduce the time employed in data collection, make more efficient workflows and enhance design efficiency, in order to delete the complexity associated with sharing a scanner among a big amount of surveyors

2.1.2 Laser scanning based methods

The advantage of employing laser scanning methods concerns the ability of a scanner to scan many parallel lines at high speed from a single location and, hence covering wider geographic areas instead of only sections. Also, to recover 3D geometries, neither camera estimation parameters nor detection features are needed (Uggla, 2015). Airplanes and helicopters are identified as the most adopted platforms to capture laser scanner data over extended areas. There are essentially two basic types of them: airborne and terrestrial.

In the first type, ALS - Airborne Laser Scanning data, the system is installed above a fixed-wing of an aircraft or a helicopter. The laser light is emitted toward the earth surface and returns to the airborne LIDAR (Light Detection and Ranging) sensor. Moreover, the ALS presents two types of airborne sensors: topographic and bathymetric. The topographic are mainly used in applications as hydrology, geomorphology, urban planning, landscape ecology, volumetric calculations and many others analyses. On the other hand, the bathymetric laser scanner is a type of acquisition that penetrates the water since collects both elevation and water depth providing the land-water interface. This application is mostly used for coastal engineering studies, which are fundamental for harbors, shores, and banks (Esri, 2016).

The second type, TLS – Terrestrial Laser Scanning data, gathers dense and accurate points, furnishing valid identification of objects located in an area. These types of point are useful to manage facilities, conduct highway and railway surveys and, certainly, to create 3D city models. The TLS data, as the ALS ones, includes two types of acquisition, mobile and static. In the mobile acquisition, the laser scan system is located above a moving platform, such as train, vehicles or boats. These systems consist of a sensor, cameras, GPS (Global Positioning System) and INS (Inertial Navigation System) as the airborne system, and are mostly used to analyzed road infrastructure, light poles, road signs close to roadways and rail lines. On the other hand, the static laser scan system does a collection of point clouds from a static location. The sensor is usually located above a tripod mount, laser-based ranging system, which can collect LIDAR points both for interiors and exteriors of buildings. The most common applications where laser data is employed are engineering, surveying, and archaeology (Esri, 2016).

2.1.3 Laser scanning and photogrammetry: strengths and weaknesses

Since photogrammetry and laser scanning can be currently considered as the most used methods for data acquisition, and hence to produce 3D city models, throughout the past years they have been heavily debated. A comparison between laser scanning and photogrammetry was conducted by Baltsavias in 1999. At that time, LIDAR data was still a relatively new technology, and thus considered more valuable than photogrammetry for several points. Firstly, because it is able to generate a DSM (Digital Surface Model) in urban areas; also, it has high density and high accuracy mapping, even for narrow or small objects; additionally, it can manage fast response applications since the geometry is directly recovered in laser scanning compared to photogrammetry where instead has to be derived.

A more recent comparison between laser scanning and photogrammetry was conducted in 2013 to generate DTM models in a tree-covered area. The author created two DTMs and compared the geometric accuracy (one made with LIDAR and the other with photogrammetry) over a forest in Tenerife. The model created with LIDAR was higher in terms of accuracy (Gil *et al.*, 2013). A further comparison, performed by Macay Moreira *et al.,* in 2013, regarded the use of three DSM, created respectively through airborne laser scanning, aerial photogrammetry and satellite photogrammetry, and buildings footprints, defined through a cadastral map, to reconstruct a 3D buildings model. The results obtained for all DSMs were similar, besides the DSM created from satellite photogrammetry, which seems less accurate for building heights and significantly less accurate for roof shapes. The other difference was between the aerial photogrammetry DSM and the aerial laser scanning one, where the first was significantly worse than the first in areas of high occlusion in the images, *e.g.* in narrow streets.
In the light of diverse studies described above, it can be assumed that laser scanning based methods present a greater number of strengths thanks to the results achievable through technique. Thus, this approach can be considered as the most efficient and, currently, as the most employed technique by city administrations for 3D city models generation.

The second group above mentioned for data processing and 3D city reconstruction, is based on automation and regards different methods developed in the past years to generate 3D city models, from the outdated manual to the ‘modern’ automatic.

2.1.4 Automatic, Semi-automatic and Manual methods

Since the requirements of 3D city models in the market are growing and spreading in many fields, in the past years has become necessary finding a way to generate more accurate 3D models within a less time-consuming and a low-cost process.

Traditional manual methods to create 3D city models waste a lot of time and money in manual works, such as scanning of a map to get a digital image, as the first step; then marking the digital image of the map with a 3D CAD software resulting in 2D data of building outlines. Lately, generating manually the 3D volumes extruding 2D footprints to buildings heights or modeling 3D geometries referring to drawings and images, always through 3D CAD. Among the traditional manual techniques, especially 3D CAD software is one of the most time-consuming and also, it needs to be handled by an expertise (Tunc, n.d.).

Therefore, considering the high costs needed for 3D data acquisition, due to the broad amount of data and the requirement of topologically consistent data, automatic and semi-automatic techniques seem to be the only approaches that should be employed to be conformed with users necessities (Förstner, 1999).

Any acquisition method needs a building model as a prerequisite, which in the context of a manual data acquisition process is enough, instead, in an automatic system building models have to be combined with other sources, such as images or models where the objects are data components (Förstner, 1999). However, due to the wide range of buildings structure and the diversity of forms that they present, some generic building models are employed in automatic system process to approximate exterior characteristics of two or more buildings and, consequently, make the data acquisition for those objects easier. The structuring of data, however, is the most problematic phase in building reconstruction since consists of organizing the neighborhood's connections in three-dimension, *e.g.,* the topology between different forms of a building. Given the structure, the geometric reconstruction becomes a simple task. It links simultaneously to the points and the edges in all images employed, providing realistic estimates about the precision of 3D geometries (Förstner, 1999). Therefore, the number of difficulties in structuring buildings and, more in general, the complexity of the whole automatic data acquisition process may lead to low success rates for the automatic systems. In the light of that, it can be assumed that automatic acquisition techniques are not able yet to accomplish as much success rates as the acitivity of a skilled operator can do. Semiautomatic systems, instead, benefit from both the operator's work in data interpretation, and the machines skills to efficiently manage the big amount of data. Thus, the intention is to increase the performance of systems driven by operators with the additional assistance of automatic techniques (Förstner, 1999). In brief, through an automatic approach, the construction of a 3D model is handled without the active supervision of an operator and consists of extracting buildings from aerial or satellite images by using technologies of image processing and pattern recognition in artificial intelligence. Through a semi-automatic approach, differently, the role of the operator is to supervise the extraction of 3D objects from the dataset. He could also perform manual purposes, but these are usually achieved thanks to automatic technologies. Throughout the manual approach, the operator shapes manually each object, one by one, by virtue of a CAD product (Pal Singh *et al.* 2013).

After these analyses, it can be argued that automatic techniques for building extraction have shown a good potential to generate 3D city models of high fidelity. On the other hand, they are not still enough autonomous to be employed alone, but they need the assistance of operators. For this reasons, semiautomatic systems can be currently considered as one of the most effective technique in data acquisition.

2.2 Data sources

The 3D city model generation process, as aforesaid, consists of combining together different information, where each of them has different formats and characteristics since it has been acquired by different methods and various procedures. Additionally, to be able to combine the data and then create the 3D model desired, is necessary knowing the wide spectrum of data formats commonly joined together by virtue of software to shape a model. During the model reconstruction process, taking into consideration all the different features that characterize each file, *e.g.,* multiple file formats, various accuracies, coordinate systems and level of details, is needed. Otherwise, if these properties are not properly considered, they may affect negatively the geometrical accuracy and visual appearance of the final product. Moreover, due to different characteristics, the material has to be processed individually before integrating the different data sets together. Only once a proper basis material has been collected, the 3D city model, which contains geometrical and semantic properties, can be successfully produced (Erving *et al.* n.d.). As aforesaid, the data acquisition process and, consequently, the data processing phase, which have been carefully described in the last paragraph, are the first phase to execute in 3D city modeling. Instead, in this paragraph a detailed overview about the most employed data formats used by city administrations to shape 3D city models will be provided. Some examples concern laser, aerial and terrestrial scanning point clouds, aerial images, photographs, architectural drawings and many other data sources.

2.2.1 LIDAR point clouds

LIDAR is a remote sensing method that employs light as a pulsed laser to simplify the earth surface producing highly meticulous x, y and z measurements. These light pulses generate detailed three-dimensional information about features of earth's shape, in order to produce a big amount of point cloud data sets that can be managed, visualized and shared in different formats, using various software. LIDAR has been initially used in airborne laser mapping applications, but nowadays, is becoming known as a cost-effective 'plan B' to photogrammetry, which is instead the traditional surveying technique. A LIDAR instrument essentially consists of a laser, a scanner, and a specialized GPS receiver (NOOA, 2017). The process of LIDAR acquisition starts when the airborne laser points to a certain area on the ground and the light ray is reflected by the surface that it bumps into. In the meanwhile, a sensor records the reflected light calculating a range that, when is combined with orientation and position data, furnished, by Inertial Measurement Unit and GPS respectively, results that are detailed, dense and rich groups of points, commonly called point clouds. Each point data is post-processed after LIDAR data collection into accurate three-dimensional geo-referenced coordinates (*x, y, z*) that link to a particular point on the earth's surface where a laser pulse has been reflected. The main utilize of point clouds is to create other spatial products, such as building models and other relevant urban objects, digital elevation and terrain models (DEM and DTM) and many others applications. A LIDAR system facilitates the work of mapping professionals, allowing the analysis of either natural or human-made objects in the environments with accuracy, flexibility and precision (NOOA, 2017).

LIDAR attribute	Description
Intensity	The return strengths of the laser pulse that has generated the LIDAR point.
Return number	An emitted laser pulse that can have up to five returns depending on the capabilities of the laser scanner.
Point classification	Each LIDAR point, which is post-processed, may have a classification in categories, which define the type of object that has reflected the laser pulse.
Edge of flight line	The points are symbolized through a value of 0 or 1. The points located at the edge of the flight line are linked with the value 1, and all the others with the value 0.
RGB	Red, green and blue bands are attributed to LIDAR data. This attribution comes from imagery collected at the same time as the LIDAR survey.
GPS time	It defines when the laser point was emitted from the aircraft. The time is in GPS seconds of the week.
Scan angle	It is a value in degrees between -90 and +90, where at 0 degrees, the laser pulse has the direction below the aircraft at nadir. At -90 is to the left side of the aircraft and at +90 to the right one
Scan direction	It is the direction the laser scanning mirror was traveling at the time of the output laser pulse.

Table 1: LIDAR point attributes (ESRI,

Additional information is recorded in parallel *with x, y* and *z* values. Indeed, intensity, return number, point classification values, points at the edge of the flight line, RGB (red, green and blue), GPS time, scan angle and direction are attributes maintained for each laser pulse recorded. In the table 1 shown in the last page, the attributes that can be provided with each point are singularly described (ESRI, 2016).

A constructive example of LIDAR employment has been implemented in Brussels, Belgium, with the creation of a three-dimensional city model for the same city, using LIDAR point cloud data. Avineon India, an international firm specialized in delivering information technology, geospatial, and engineering support services has been appointed for this high budget project (4.5 million). It was expected with a combination of laser scanning and 2D mapping to shape more than 260.000 buildings and 2 bridges in GML format with LoD2, where one of the major challenges was the data integration phase that, from a broad variety of sources, had to maintain their geometric, topologic, semantic and visual features (Bentley, 2017). As aforesaid, the traditional method to create a high-accuracy 3D city model would have been using photogrammetry with stereo compilation, but, in this case, it would have wasted too much time and money. For this reason, Avineon India employed a combination of Bentley Map[3] and MicroStation[4] to produce a detailed 3D model from LIDAR, orthophotos, oblique images, DTMs, stereo compilation and vectored datasets. Thanks to the use of Bentley Map, the project costs have been reduced compared with standard costs of traditional photogrammetry approaches. Indeed, MicroStation has allowed the company to integrate and load data from different sources and to further process and enhance the data within the Bentley world. Moreover, the model has been saved in CityGML output, which is more feasible, without loss of spatial and attribute accuracy. Lately, combining the tools and the different data formats mentioned above, Avineon has been able to generate detailed models of complex roofs and bridges with positional and vertical accuracy (Bentley, 2013).

LIDAR has recently become a quite fundamental information source for generating high-quality 3D digital surface and building models since it allows an aircraft to briefly gather

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[3] *Bentley Map:* is an extension from Bentley that runs on top of MicroStation adding GIS and spatial capabilities to the CAD program. Retrieved in https://en.wikipedia.org/wiki/Bentley_Systems

[4] *MicroStation*: is a CAD software product for 2D and 3D design and drafting, developed and sold by Bentley systems. "It provides the power and versatility to precisely view, model, document, and visualize information-rich 2D and 3D designs of all types and scales for professionals in every discipline on infrastructure projects of every type". Retrieved in: https://www.bentley.com/en/products/brands/microstation

heights of a field in a large area with the accuracy of centimeters in height and sub-meter in ground position. Therefore, thanks to its advantages, LIDAR can be considered an active approach for reliable 3D determination, which provides a productive way to collect models for a large urban site (Hu *et al.,* n.d.).

2.2.2 *Oblique images*

Aerial imagery is for municipalities a fundamental support in geospatial and thematic information extraction as well as in planning processes. Until recent times, only orthophotos produced by nadir[5] aerial images were used for these purposes. However, current cases of urban damage assessment, land planning and 3D cartography have demonstrated the high value of these type of images. The development of oblique image cameras has opened up new possibilities in this field, for instance, the inclusion of oblique images for the extraction of 3D value-added products, which has contributed to the growth of their importance today. Indeed, since 2000's, oblique cameras have been used for several applications, such as tridimensional visualization of urban objects (buildings, roofs, façades) from a 360° perspective, texturing of 3D city models and measurement of building heights (Poli *et al.,* 2017). The advantage of catching images from an oblique perspective is the possibility to see elements that usually could not be seen from vertical views, why occluded by vegetation or higher obstacles. Indeed, by virtue of this type of data, there is an additional perspective that allows viewing objects, road edges and lower building sides. Another advantage is the higher degree of image overlap, which facilitates the generation of dense point clouds and production of more realistic orthophotos. These clarify the reasons why the number of requests by municipalities for aerial photogrammetric flights using oblique cameras is growing (Poli *et al.,* 2017).

However, before implementing new technologies like oblique cameras, especially in small municipalities, there is an important cost-benefit analysis that has to be done. When evaluating the cost of the flights, which usually depends on the settlement structure and on the dimension of the area to measure, additionally, it is necessary taking into consideration that an aerial photogrammetric flight with oblique cameras has higher costs than nadir flights. However, the employment of oblique images, if a proper measurement tool is used, may

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[5] *Nadir:* In aerial photography is the point on the ground vertically beneath the perspective center of the camera lens. Retrieved in http://support.esri.com/en/other-resources/gis-dictionary/term/nadir.

potentially reduce the area survey and transfer part of the surveying operations to the office. For instance, at AVT, an Austrian company that conducts flights with a hi-tech camera, the flight strip overlaps are pre-planned, so that each object is captured on an average of six to ten images in each viewing direction (Poli *et al.,* 2017).

Furthermore, there are others factors to take care of before the implementation of this support tool. Indeed, in addition to the aerial oblique images themselves, municipalities need certain programs to read the images and to extract the 3D measurements from the data collected. Usability, in fact, is another fundamental question to take into consideration, because, frequently in small municipalities geo-information is managed by staff, whose do not always have an educational background in GIS and surveying. To facilitate the requirements for images visualization and mapping, AVT, for instance, has developed a software called 'Geobly', shown below in figure 7, which the company itself uses for high-precision oblique surveys (Poli *et al.,* 2017).

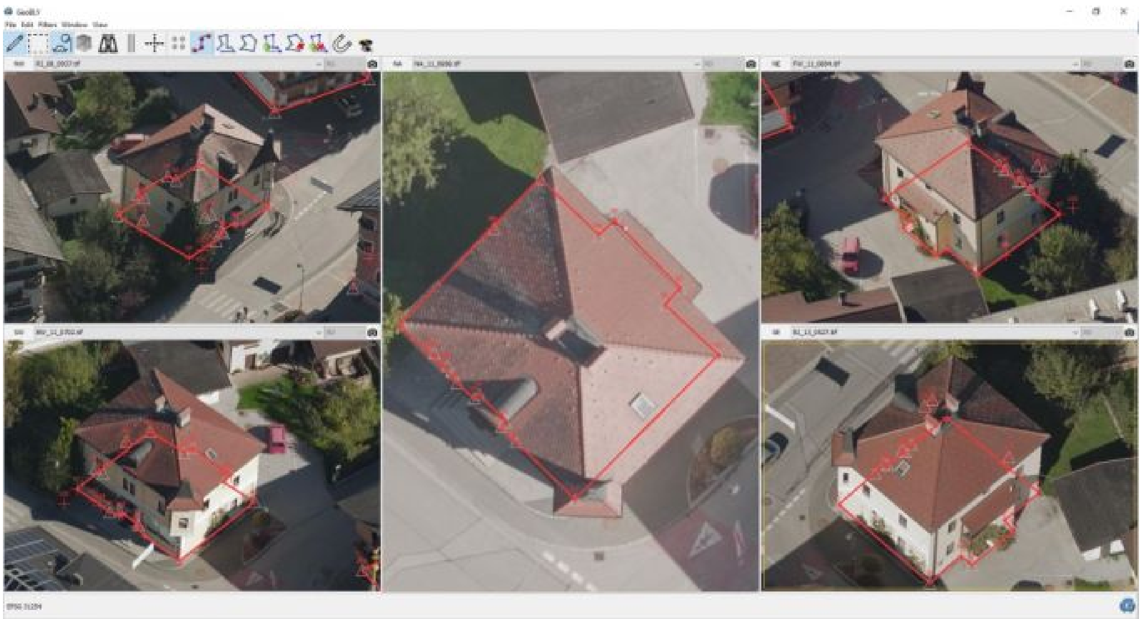

Figure 7: Visualization of buildings in Geobly software. The façade is visible in the oblique images, but not in the nadir one (Poli et al., 2017).

These additional values of oblique imagery are highly correlated to urban mapping and management, as it has been demonstrated in Kundl, a small town in Austria. Kundl is a town located in a region with a strong economy, where the population and, hence construction of alive activities, are growing. The civil authorities have planned the flight with an oblique digital camera, aiming to collect, besides standard photogrammetric products, *e.g.,* DTM or orthophotos, a comprehensive basic data for the municipality and a clear visualization of all objects from several perspectives, as it is shown in the next page in figure 8.

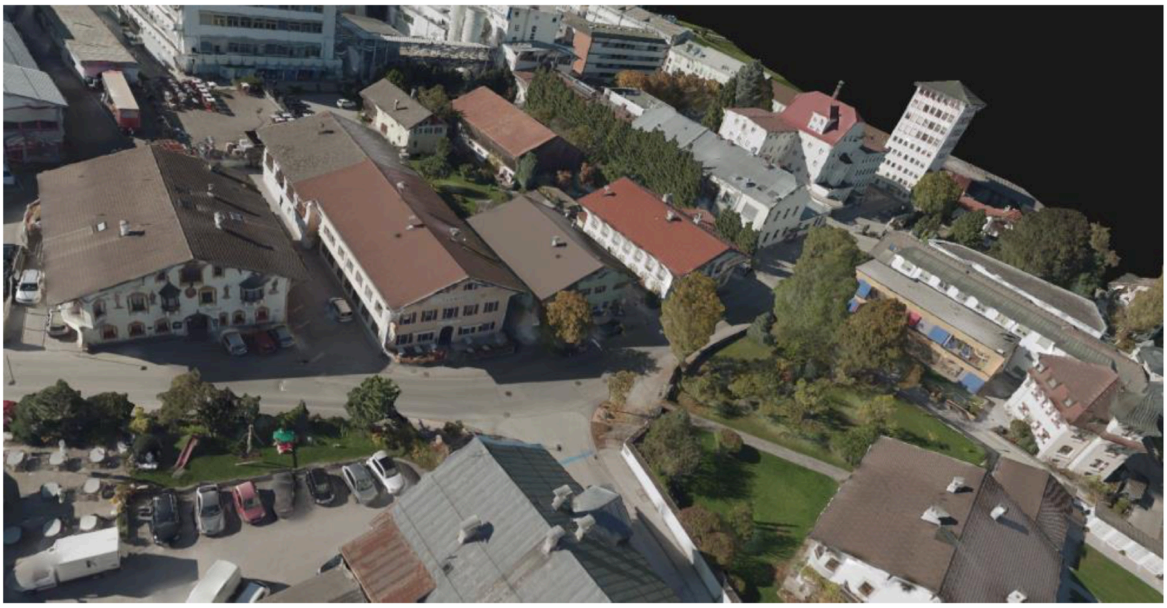

Figure 8: Visualization of the oblique image of the city of Kundl, Austria (ISPRS, 2017).

Oblique images have been used by the town of Kundl for several applications, such as planned changes for buildings, which are documented and reviewed; the analysis of the building structure, to gather helpful information for planning activities, *e.g.* the number of floors and heights of buildings and to benefit the activity of urban planners and building engineers; also for the mapping of traffic signs, both vertical and terrestrial, which are easily recognizable in the images. Lately, the town of Kundl has planned to employ the oblique image results in city planning tasks as well as in location marketing to design virtual tours (Poli *et al.* 2017).

Another type of a widespread aerial oblique image is BlomOBLIQUE, owned by Blom, a service provider that has primary business in aerial photography, laser scanning, mapping, modeling, databases and many others applications. As Geobly, this oblique image has several functionalities, such as the ability to measure heights, lengths and area's features, in order to integrate vector data over the oblique imagery. BlomOBLIQUE has recently captured almost every city in Western Europe with at least a population of 50.000 inhabitants. Hence, it can be considered as the most comprehensive imagery database today available in Europe (BlomASA, 2017). For instance, a Blom oblique image has been recently integrated in the web-GIS portal of the city of Bologna. Indeed, combined with the interactive mapping of several urban plans at the city level (PSC, RUE, POC) the oblique image has been implemented as a public consultation service available online, employed to inspect and measure different objects on the map, in order to let users export screenshots about the areas they are interested in, as it is shown below in figure 9.

Figure 9: On the left: Blom oblique image of the city of Bologna zoomed on *Piazza Maggiore.* On the right: Vertical image zoomed on the same area of Bologna (Comune di Bologna, 2017).

A further value that most of the oblique images commonly employed may provide combined with other planning tools, is connected with earthquake damage assessment. Indeed, for instance, this type of imagery has been beneficial for the town of Norcia, in Italy. After an earthquake in 2016, which has deeply damaged the town, AVT has executed an aerial flight for the energy company Engie Italia, and captured aerial images from five angles perspective. Aiming to generate a 3D model that represented the emergency areas, a new strategy to acquire oblique images has been successfully tested, which consists of combining nadir camera with focal length and a flight plan with two overlapping blocks. The 3D surface model of the damaged areas allowed identifying the collapsed parts of the buildings and the ruins in detail on the ground. Hence, by virtue of the oblique views of the ruined area, even narrow alleys were distinctly visible and thus, easily editable. Moreover, a detailed assessment of the damage was feasible thanks to the measurement of distances, zones, and volumes (Poli *et al.,* 2017).

Therefore, after having analyzed oblique imagery's pros and cons and the case of studies described above, it can be argued that oblique aerial images furnish detailed, quick and clear recording of spatial data, which can be easily elaborated into the office. Additionally, the easy identification of urban objects and simple comprehension for employees, compared to nadir surveys, has proved their value for municipalities (Poli *et al.,* 2017).

2.3 Software employment in 3D modeling

Nowadays, various mapping tools are frequently employed by industries, firms and, mainly, city administration departments with the aim of creating detailed 3D city models, which can provide accurate geographical representation of whole cities, in order to allow users to interact with the models recovering specific objects information (Truong-Hong *et al.,* 2013). Since 3D models are significant components of digital productions, the choice of the right software for 3D models generation is truly important, but often can be quite problematic because of the wide range of different features that each application requests. Indeed, which technique is used to create a 3D city model depends on the application and on the level of details of the resulting model. Another issue concerns openness and the level of accessibility that software have for their users. Generally, programs that enable to manage different data formats together are developed from several software industries and are very expansive. In the past years, the decrease of available resources has driven both researchers and users, involved in various fields, to consider open-source software for 3D city models tasks. Indeed, today there are numerous open-source 3D modeling software available and qualified to manage point clouds data, aerial images, orthophotos, meshes, textures and many others formats (Bonfanti *et al.*, 2013).

An example of open-source software is Blender. This product is currently one of the most popular and employed open-source 3D graphics applications. It was originally developed by the firm Not a Number (NaN) and has kept on as free software. Today, a large community of users has a strong activity promoted on several blogs for sharing information, data, scripts, and FAQ, about user's struggles with 3D modeling. Blender is an integrated application that provides a wide variety of modeling, texturing, animation, simulation rendering and post-processing functionalities in one package, enabling the production of different 2D and 3D data formats. It has an open architecture that furnishes interoperability, flexibility, and use of integrated workflows (Bonfanti *et al.*, 2013). However, even though users can acquire a big amount of modeling information both from the software itself and the user community, it cannot be considered as an easy and intuitive software to use since even only for the comprehension of preliminary modeling operation or of the working principles of available tools, it needs a time-consuming procedure to be understood.

The number of applications where programs are employed has increased rapidly in the past years, both for open-source and commercial software, with examples being found in location-based services, visualization for city planning, and many other fields. At present, there are various software available in the market for 3D city model generation, which are based on: computer-aided design (CAD) as Revit, owned by Autodesk; Virtual Reality Markup Language (VRML); Keyhole Markup Language (KML) architectures; photogrammetric techniques; and software that can be used for texturing 3D models (Truong-Hong *et al.* 2013).

For instance, BIM software as Autodesk Revit, provides tools to develop accurate high-quality architectural design. Numerous other software that generate models according to photogrammetry principles and need as input only different format of images, such as ContextCapture, Pix4D or Leica Photogrammetry Suite (LPS). On the other hand, several software, which among the broad variety of functions that they own, have the ability of texture a building model that already exists. Also, most of these software, process automatically the texturing and only in few of them is necessary manually sticking on the texture to the corresponding façade. An effective example is ESRI CityEngine, but even Sketchup and Photoshop (Ivarsson, 2014). However, throughout the 3D model generation process, can be also used diverse types of software that not necessary have to identified as 3D modeling products, but in any case, they are able to handle and combine different data formats together and, consequently, generate detailed 3D city models. For instance, FME is a perfect example for software that works in this way.

2.3.1 Autodesk Revit

Revit is a design platform, developed by Autodesk, for building information modeling (BIM) since provides to users information about project design, measures, scope and phases based on their needs. Furthermore, with its powerful tools Revit lets users utilize the model-based process to design, build, plan and, more in general, manage buildings and infrastructure. Indeed, users have the possibility to easily design a building within its structure and components in 3D, annotate the model with 2D drafting elements, and access building information from the building model's database (Autodesk Revit, 2017). Also, as it is shown in the next page in figure 10, Revit supports a multifunction design process within a collaborative design.

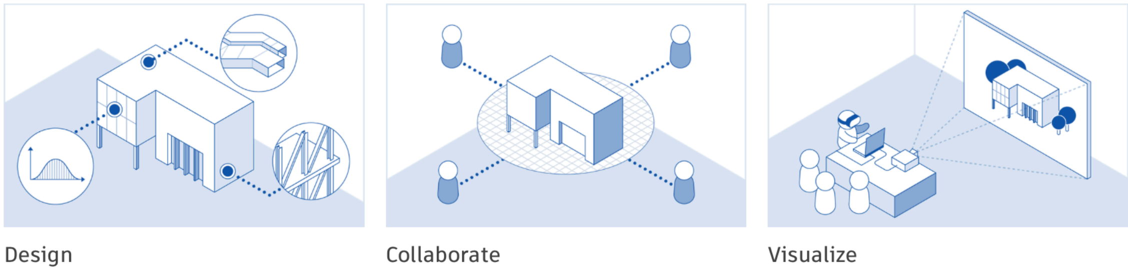

Figure 10: Multifunction design process provided by Autodesk Revit. (Autodesk Revit, 2017).

The Design phase concerns the editing and analysis of the building components and structures. The Collaborate phase, regards the ability provided to multiple projects contributors to have access to shared models, reducing clashes and rework. Lastly, the Visualize phase, allows to better show the design intent to project owners by the use of models, which creates high-impact in 3D visualizations (Autodesk Revit, 2017).

Throughout the modeling phase, each drawing page, either 2D or 3D, is a representation of information from the same virtual building model. Indeed, while a user is working on a building model, Revit gathers information about the building project and orders the former across all other representations of the project. In other words, every change made to one view is instantly visible in all other views of the model, keeping also the views synchronized all the times. The relationships among all the elements in a project are created either automatically by the software or by users when they work (Autodesk Revit, 2017).

2.3.2 ContextCapture

ContextCapture might be considered an effective example of those kinds of software that generate models according to photogrammetry principles. This product is a commercial software developed and sold by Acute3D, a Bentley Systems company, and that comes from the former Smart3DCapture technology. This software works without any human interaction and uses high-resolution images as input creating 3D city models, as it is shown in the next page in figure 11. During the producing phase, ContextCapture automatically analyzes several images of static subjects, taken from various viewpoints, identifying those pixels that correspond to the same physical points. Thanks to the correspondences, which work as benchmarks, the relative orientations of images and accurate 3D shapes of the scene can be deduced. This program, by virtue of cutting edge photogrammetry, computational geometry algorithms, scalability, efficiency and interoperability, solves many problems, especially in terms of time-consuming. Another advantage concerns the use of a simple camera, rather than an expansive special device, as it happens in 3D scanning. Furthermore, besides the production of dense point clouds, which usually need to be analyzed and processed with third peculiar software, ContextCapture can also provide a textured 3D triangular mesh, which is more manageable to be displayed or edited (Acute3D, 2017).

Figure 11: Screenshot of KTH University 3D model, reconstructed from aerial images in Smart3DCapture (Ivarsson, 2014).

2.3.3 Pix4D

Pix4D is a photogrammetry and drone-mapping software that uses images to generate multiple results, such as orthomosaics, highly point clouds, models and many others formats. This software presents a unique Mobile+Desktop+Cloud workflow, which in four steps allows flexible processing options. As it is shown in the next page in figure 10, the first is the Capture phase, during when can be used any image or Pix4Dcapture, a flight planning app for drone operations or flight review. The second phase is the Process, which can work offline on Pix4Ddesktop for full control over data, or online for hardware free results, automated on Pix4Dcloud. The third step is the Analyze, which, for the desktop, concerns the use of advanced features for editing and measurements, and for the cloud, monitor projects and use the drawing overlay for construction. The last step provides the possibility to collaborate on online projects, share maps and models with an URL (Pix4D, 2017).

Figure 12: Workflow to create and then share 2D maps or 3D models, where the input is an image captured (Pix4D, 2017).

Two of the most important products that belong to Pix4D industry are Pix4Dmapper and Pix4Dmodel. Pix4Dmapper processes, automatically, terrestrial and aerial imagery, acquired by any aircraft or UAV (Unmanned Aerial Vehicle) using its technologies, in order to convert images into high definition, geo-referenced 2D maps and 3D models, which are customizable and timely results for a broad spectrum of software and applications. Pix4Dmodel is mainly used to create photorealistic and textured 3D models processing drone images. By virtue of its features this software is able to distinguish elements, calculate distances and surface areas, in order to add and share these data on the Cloud. Additionally, with this product is possible creating a fly-through path for a 3D video that, for instance, shows the project created to potential clients, or that can be also posted on Vimeo, YouTube and many other platforms.

2.3.4 Leica Photogrammetry Suite (LPS)

LPS (formerly known as Leica Photgrammetry Suite) is a software application employed to perform photogrammetric operations on imagery from which information is extracted to generate terrain models, produce orthophotos and extrude 3D features. LPS is commonly used to process aerial and satellite imagery creating the types of geospatial data aforementioned. The approach employed by this photogrammetric application may involve remote sensing satellites, airborne cameras or ground-based cameras (GIM, 2017).

For instance, if the context of interest regards airborne cameras, the workflow would concern the scanning of the imagery, with the creation of a digital version of it, that would solve the orientation parameters, and thus, triangulating the images. Once do that, the system can generate, automatically, DTMs, that then in turns, will be orthorectified, which means an aerial photograph geometrically corrected, such that scale is uniform (GIM, 2017.). This leading photogrammetric application is widespread used by numerous national and regional mapping agencies, and commercial mapping firms as well as academic research.

2.3.5 Esri CityEngine

Esri CityEngine presents many 'easy-to-use' editing tools that allow users to briefly sketching and texturing on 3D building models. For instance, intuitive tools for the preparation of façade textures through ground-based façade images, perspective adjustments, and region selection can be all executed in one step. This product is a stand-alone software produced by Esri that, besides texturing functions, gives to users the chance of creating 3D cities in few steps based on their already existing 2D or 3D GIS data that, lastly, can be shared on the web for sharing 3D models, analyses and design proposals with decision makers, as it shown below in figure 13 (CityEngine, 2017).

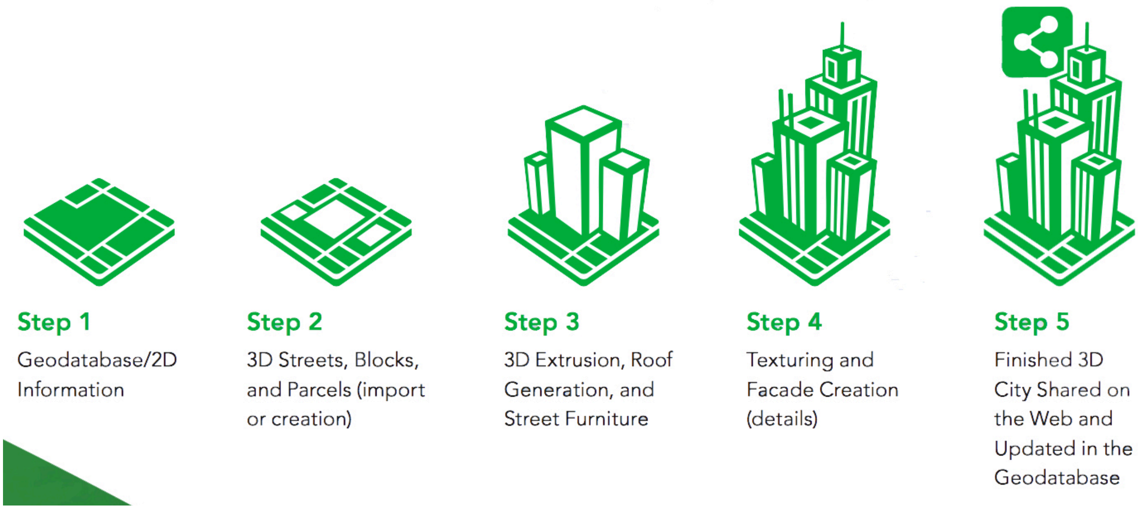

Figure 13: Workflow to create 3D cities from existing 2D/3D GIS data (CityEngine, 2017).

Additionally one of the key strengths of CityEngine is its possibility to visualize, analyze and store zoning regulations in three-dimensions, which are text-based descriptions of allowed building volumes, density and usage. Even if it may appear hard to understand for the public, this tool helps to depict the image of a city in terms of growth and development (CityEngine, 2017).

2.3.6 FME

FME (Feature Manipulation Engine) is a software mainly used as integration platform that easily connects numerous systems, transform data from and to hundreds of different formats and automates workspaces. This product supports over 350 file formats and applications preserving data quality during the conversion process, web services, and moreover, provides a strong support for location data, such as GIS, CAD and BIM, plus with a library of over 5.000 coordinate systems (Safe Software, 2017).

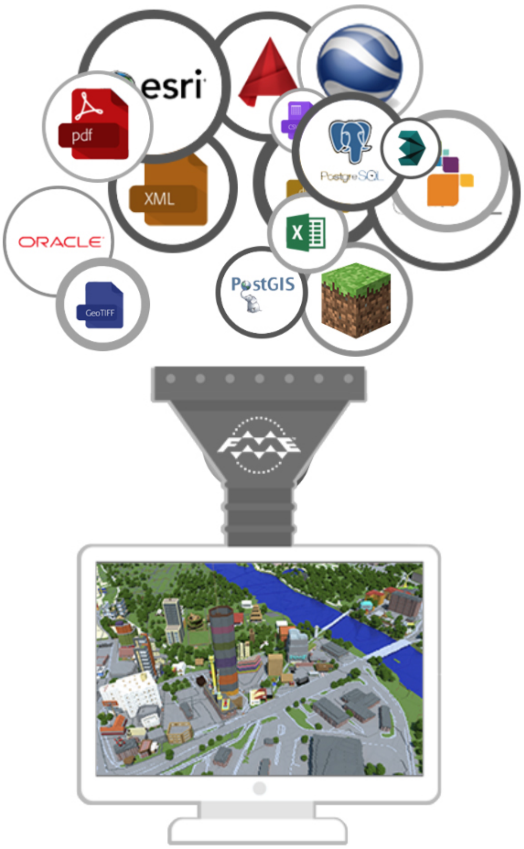

Figure 14: Combination of diverse file formats for 3D model generation (Safe Software, 2017).

FME works essentially with three products and each of them has different functions. FME Desktop has the role of integrating different data formats, as it is shown in the last page in figure 14. It uses a visual interface, called workspace, where, within different bookmarks, the files are connected and the data transformed. Each workspace is repeatable, hence, it can be run again and again. FME Server works hand-in-hand with FME Desktop and is used to automate virtually any data task. It provides enterprise automation and allows users to run workspace in real-time, as an answer to triggers and requests and according to any schedule. FME Clouds, lately, is used to connect the applications to the Cloud. It combines the flexibility of the Cloud with the automation power of FME Server (Safe Software, 2017). Additionally, FME supports the reading and editing of many 3D formats. Several data formats, such as LIDAR, 2D footprints, aerial images, DTM, DSM and many other formats typically used to shape three-dimensions models, can be combined together and, thanks to a wide spectrum of transformers that can shape or alter these data, diverse LoD 3D city models can be created.

The 3D city model obtained for the municipality of Vaxholm, in Sweden, has been created with FME. Through the combination of three different data formats and the usage of a wide variety of transformers, a LoD2 3D city model has been generated. The whole modeling process to create the 3D model will be explained more in depth in the next chapter.

2.4 3D Visualization

In the light of the different approaches described in last paragraphs, it can be argued that the 3D city models generation can occur as a time-consuming and complicated process that involves several phases. As aforesaid, the first step is data acquisition, performed according to the required level of details of the model. Successively, the files recovered are stored in a database, the schema of which depends on the requirements and applications where the model will be employed. After having chosen the most feasible software to accomplish the results predefined, the data acquired are combined together and through several mapping tools, the 3D city model is generated within all its details. Lately, the 3D model can be visualized thanks to various application platforms (SBL, 2016).

Typically, 3D city models rendering and visualization are fast and cost-effective phases, which can be achieved through a wide variety of techniques. However, visualization can be considered as a big challenge since 3D city models components mostly come from different data sources, for instance, geodata, GIS data, CAD and many others mentioned in the last paragraphs. For this reason, a common framework schema suitable for all the components of the model and based on its requirements, should be established beforehand (SBL, 2016). In the light of that, to accomplish the last phase of 3D city model generation process, the main goal is, firstly, considering the wide range of 3D visualization techniques available, and then choosing among them, which one is the most efficient and appropriate for a set of heterogeneous data that have to be visualized together in the same 3D city model, in order to perform a given purpose in a certain context. Therefore, the selection of an effective visualization technique for a 3D city model is important for the choice of the right platform to view abstract information of a 3D city model, and on the other hand, it is a difficult task due to the large number of criteria that have to be considered in advance. This means that the technique chosen must be able to display the desired information, such as support efficiently user's tasks and do not interfere negatively, for example hiding or altering information (Métral *et al.*, 2012).

Virtual 3D models are used in several applications that normally go far beyond the mere representation of geometric elements and visualization of city objects. Some examples of these applications concern the evaluation of urban projects in terms of visual aspects and quality of life, the estimation of the impact of a project on the surrounding landscape and on others factors. Such tasks need the visualization of data that come from different fields, *e.g.,* transport and construction; from different types, *e.g.,* measures of noise; that have different scales and take different forms (Métral *et al.*, 2012). Each application, among this broad spectrum, requires rich information models, which associates to urban entities, in addition to their geometric properties, present other types of abstract information connected to the city environment (Métral *et al.,* 2012). Abstract information means all files that cannot be viewed without a visual abstraction that instead, has to be shown to users. Essentially, visualizing a semantically enriched 3D model means displaying the geometric properties of the questioned model, in other words the geometry of spatial objects, and also, depicting the objects that represent the enrichment information associated with those objects. (Métral & Falquet, 2015). Furthermore, these applications to find the most appropriate visualization technique, need to consider a set of criteria, such as the data types to depict, the features of the task that has to be performed by the users and the spatial configuration of the considered context (Métral *et al.*, 2012).

The existing literature about application fields of 3D city models is quite unclear and does not describe properly and explicitly visualization techniques, focusing more on the 3D models generation process. Thus, it is problematic to individuate a certain technique that fits for a 3D model or even make a comparison between different techniques according to specifics criteria. For this reason, visualization techniques face diverse issues: for example, when a 3D city model is employed for a complex application it can imply visualizing different data formats at once; or if a technique results feasible and efficient when it is used singularly, it does not mean that some incompatibilities will not come up when the same technique is combined with others (Métral *et al.,* 2012); also, the diversification of file formats that have to be displayed, implies more possibilities of associated visualization techniques usage; data that have to be visualized as a whole by a set of visualization techniques can lead to an integrated visualization (Métral et al., 2012). Furthermore, not only visualization techniques have big limitations to handle heterogeneous data, indeed, even current geodata-oriented tools, for instance, ArcGIS, have limited 3D competences and limited sets of visualization techniques.

Considering the broad amount of visualization techniques that have been developed during the past years and the spectrum of data formats, tasks, different users and visual contexts, it can be assumed that the selection of the optimal visualization technique is far from trivial. Aiming to verify in which task and to which context a technique can result relevant, the work carried out by some techniques is normally pre-tested. However, the evaluation results are not usually publicly available, even though they can actually be truly helpful to select in the future a technique employed for similar tasks (Métral *et al.*, 2012).

An example of an internationally widespread 3D visualizations platform that concerns urban planning applications, is Agency9, a Swedish SME (Small and Medium-Sized Enterprise) founded in 2003 specialized in 3D web-based solutions, and that in next chapter will be properly described introducing several cases of study where it has been employed.

2.4.1 Agency9 CityPlanner

The company Agency9 initially was designed for gaming industry and only in a later time has moved towards urban planning solutions, integrating GIS and spatial support to its 3D components and developing its main product, CityPlanner, a user friendly solution which provides easy-to-use visualization tools to support dialogue with the public (Eurisy, 2014).

Indeed, Agency9 CityPlanner is a web-based service for 3D visualizations that provides three-dimension web planning interactive tools to create, share and display projects and spatial information within a regular web browser, without using additional software. Municipalities, private organizations and autorithies are able to use photo-realistic 3D models visualized in CityPlanner for application fields as local planning, urban development, infrastructure and energy, in order to communicate, engage and get citizens interested in the planning process, enabling web publishing of 3D plan visualizations, and at the same time, prepare them to the new changes planned in the environment where they live, as it is shown in the next page in figure 15. Additionally, citizens can express their proposals directly on the map, logging into their personal account (Gakstatter, 2013).

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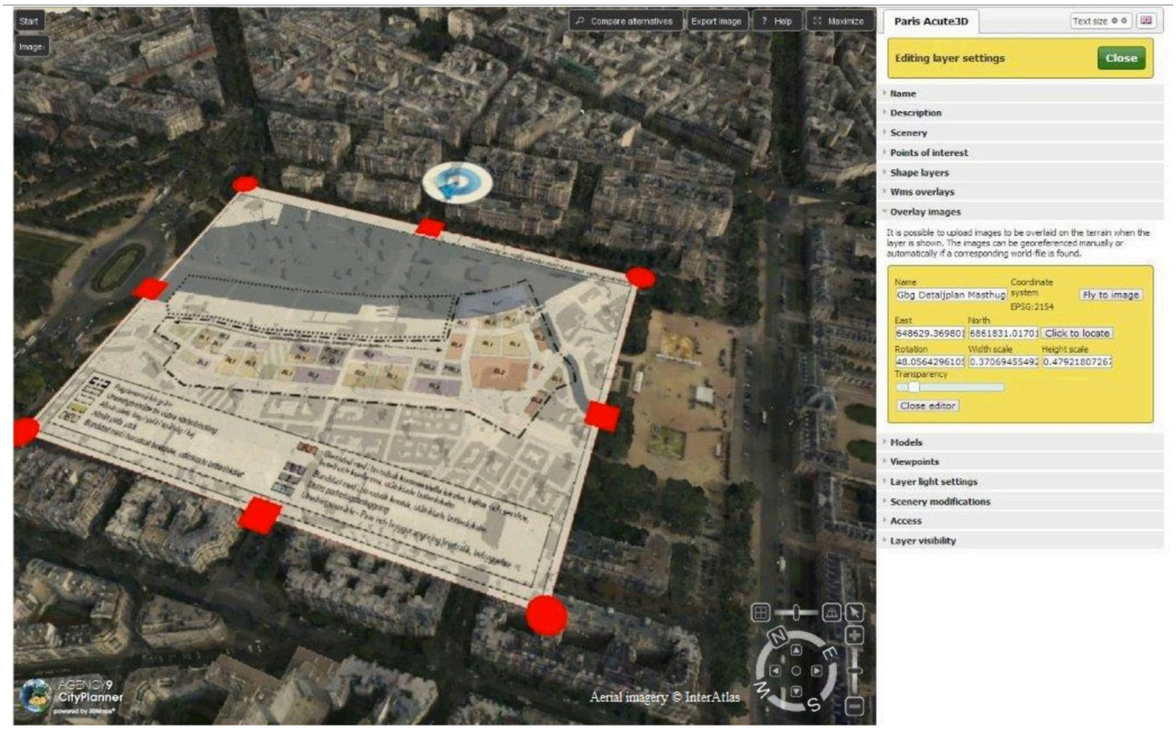

Figure 15: Visualization of an aerial imagery of Paris where a Detailed plan is clamped on the area of interest (Gakstatter, 2013).

Chapter 3

Application of a 3D model in a Swedish municipality

3.1 Study area: Public use of 3D city models in Sweden

In Sweden, the traditions of independence and self-government at the local level have ancient roots (Newman & Thornley, 1996). In 1970, as consequence of the decentralization process, the central government transferred a considerable amount of political responsibility to counties and especially to municipalities. Indeed, territorial and urban planning are managed by the public sector and municipalities, who are the main actors, and also are matters of municipal interest. On the other hand, at the national and regional levels, only official documents and guidelines are produced and their main concern is the whole country's development. However, in general, these levels cannot be considered as strong actors. Therefore, at the local level, the 'Planning Monopoly' can decide for its citizens on matters of common interest, holding primary responsibility for the planning and protection about land-use within a legal framework and under the supervision of the national government (Solly, 2013).

In the light of this historical background, nowadays, the 3D industry in Sweden is increasingly developing thanks to the recurring employment in of 3D models in public use and particularly in city planning applications widespread in many municipalities. Indeed, many Swedish cities are currently engaged in projects that aim to reinvent the use of 3D city models for the promotion of the city development and public participation (GIM, 2015). Moreover, broad fields of 3D city model's users are municipalities. Either with more advanced or basic procedure, most of the of city administration departments have already adopted or are in the process of setting up 3D city models as part of the range of their planning tools. For instance, in 2015, a digital dialogue was implemented for a massive development project in Stockholm, in the area of Norra Djurgårdsstaden. In this context there is currently a ongoing complex process of rehabilitation, aiming to change the former use of industrial sites towards the densification of the urban structure. Hence, the project will host a wide range of homes, services and businesses, strategic infrastructures and an international port, called Royal Sea Port. Furthermore, Norra Djurgårdsstaden aims to become a green community with sustainable urban development and homes with innovative energy technologies (Solly, 2013).

Figure 16: Project area with its sourrounding districts (Stockholms Stad, 2016)

Above in figure 16 is shown the area of interest. For a project with this size, the voice of the citizens was considered fundamental to achieve the goals planned. Therefore, in the early phase of the project, the city planning department has encouraged citizens to share some ideas and proposals. The digital dialogue's structure consisted essentially of a link, available for every user interested on Stockholm city's web page, which uses the 3D city model (about 500 square kilometers) as background. The 3D model, shown below in figure 17, employing Agency9 technologies, has been streamed to web, tables and exhibition screens (GIM, 2015).

Figure 17: The 3D model of Norra Djurgårdsstaden area visualized in City Planner (Agency9, 2015).

Another projects, in Sweden, that aims to reinvent the use of 3D city models for the promotion of the city development and public participation has been promoted by the city of Gothenburg in 2015. The city administration has re-launched its citizen portal *Min Stad* (My City) with new functions, a portal that encouraged citizens to post ideas, according to their needs, that can result useful for the development and enhancement of Gothenburg. This portal started to be operational since 2012 and has captured the attention of many visitors as well as thousands of proposals from citizens (GIM, 2015). The model is shown below in figure 18.

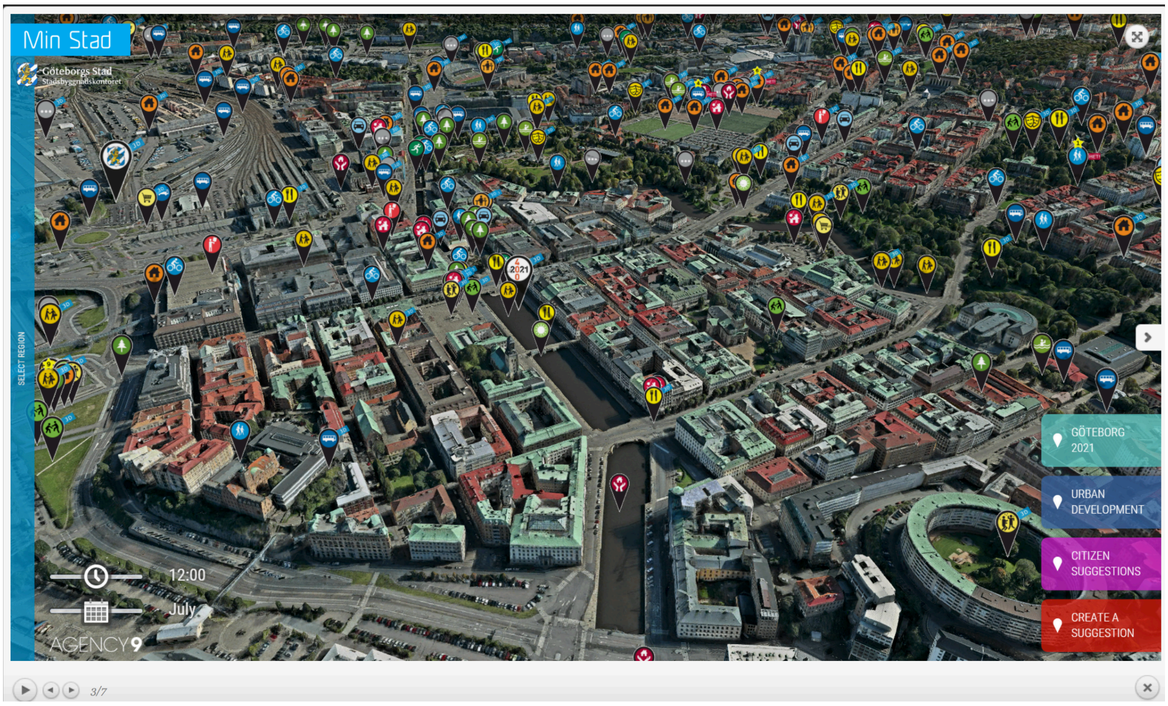

Figure 18: The *Min Stad* portal of Gothenburg visualized in CityPlanner (Agency9, 2015).

A further example in Sweden concerns a marketing campaign that has been taken forward by the city of Linköping. By virtue of the employment of 3D visualizations of the city on a big touchscreen, the improvement and development of the city have been promoted. At the same way shown in the previous projects, the 3D city model has been used as background, as shown in the next page in figure 19; In this case also, several projects, themes and proposals were presented through animated models and graphs (GIM, 2015).

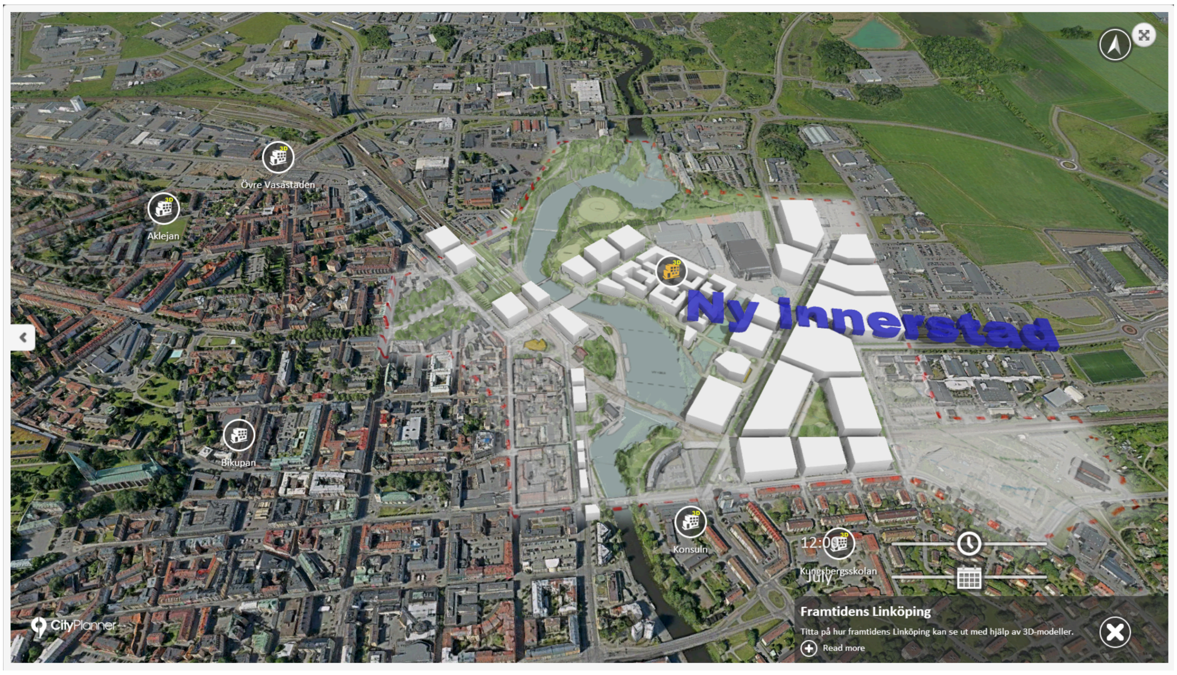

Figure 19: Touchscreen of Linköping's 3D city model visualized in City Planner (Agency9, 2015).

In the light of the cases of study analyzed above, the broad employment of 3D city models for public uses and stakeholders engagement, during the past years, have allowed many cities in Sweden to digitally promote the implementation of new projects in their territory as well as inviting an increasingly number of citizens to take part at decision-making process.

3.1.1 *City of Stockholm: how a smart city develops*

Stockholm is the capital of its own county (*Län*) and it is considered as the hearth of the Swedish economy since it is the most populous region and the most densely populated area in contrast with the rest of the country (Solly, 2013).

Besides the ongoing project in Norra Djurgårdsstaden, a few years ago the city of Stockholm has thought up a productive as well as popular way to publicly divulge its future projects. *Kulturhuset* (Culture house) is a center for arts and culture that hosts a theater, exhibitions, libraries, seminars, events, restaurants and cafés and that represents a popular hangout in the city center, during the day, for tourists and locals (Visit Stockholm, n.d.). Inside this meeting place, it has been installed a large interactive touch screen available for visitors to fly through a photo-realistic 3D model of the city and, at the same time, explore all the projects currently planned in Stockholm municipality (Acute3D, 2014). Two interactive touch screens are part of a permanent exhibition, called *The Stockholm Room*, which, besides the model, includes themed weeks, workshops, meetings and press screenings about several topics, such as traffic, accessibility, environment, sustainable building and new construction projects. Moreover, the screens show a 3D model supplemented with information about planned or ongoing construction projects, as it is show below in figure 20, in order to depict different aspects of how the city is growing.

Figure 20: Touchscreen of Stockholm's 3D city model visualized in City Planner (BlomASA, 2014)

This virtual model has been commissioned by the city of Stockholm to Blom Sweden AB aiming to create a realistic 3D model that covered 500 square km of the urban area, in order to show the city's growth and allow residents and users to visualize the impact that proposed new projects may have on the urban area, in an accessible and interactive environment. Blom used Smart3DCapture for 3D reconstruction, ensuring automate modeling and providing a tool throughout the planning process. Also for the visualization has been employed Agency9 CityPlanner, furnishing a powerful visualization tool to have a clear vision of each project part of the model (Bentley, 2015). Therefore, this virtual and interactive 3D model cannot be considered as a mere 3D visualization of Stockholm, but rather, as a quite smart key tool that can be used during the decision-making process and that allows a fast and easy communication with citizens about future developments.

3.1.2 Vaxholm in the Stockholm County's context

The territorial entities in Sweden consist of 21 *Län* (formally Counties) at the regional level, whose main purpose is to promote regional development, growth, transport and environmental protection. At the local level, instead, Sweden is divided in 290 *Kommuner* (municipalities), which since 1970 thanks to a decentralization process, have gained more decision-making power and responsibilities, rather than the national and regional levels. The Stockholm County is considered as the most important metropolitan area in the north Europe, which attracts many European Community funds and projects. The metropolitan area counts 2.3 million inhabitants and Stockholm is the capital of this region, with a heterogeneous landscape, from dense urban areas as well as large expanses of forests and the broad Stockholm Archipelago, which includes more than 30.000 islands. This region consists of 26 municipalities, including the city of Stockholm, as it is shown in the next page in figure 21 (Wikivoyage, n.d.).

As many others European metropolitan areas, the Stockholm County faces structural challenges due to population growth, rapid technological changes and a globalized market. These socio-economic changes are leading to an increasing demand for mobility, housing and employment, adding further pressure on infrastructure and the number of existing homes in the region (Solly, 2013). To cope with these kinds of requirements, many cities in Sweden have already adopted 3D city models for several purposes, as aforesaid, or are in the process of setting up 3D city models as part of their spatial planning tools.

Figure 21: Geographic overview of Stockholm's County (Lansstyrelsen Stockholm, 2017).

The generation of a 3D city model for the city of Vaxholm will be carried out throughout this chapter as a case study to get firsthand experience with some of the available methods, mentioned through the last chapter, to create 3D city models. The whole process to create the model, the results obtained and the potential future applications and improvements that the model may reach will be presented in this chapter. The geographic area used in this case of study is the municipality of Vaxholm, which is located in northwest of Stockholm and it is often referred as the capital of its Archipelago. Vaxholm consists of 70 islands, most of them connected by bridges, and has about 11.000 inhabitants (Vaxholms Stad, 2017).

During the second half of the XVI century, a fortress has been built by the king upon a small islet located next to Vaxön, the densest and most populated island of the municipality. Since that moment, the village started growing and became what is today, a large fleet of fishingboats. A geographic overview of the municipality and a zoom of the island of Vaxön are shown below in figure 22 and 23 respectively.

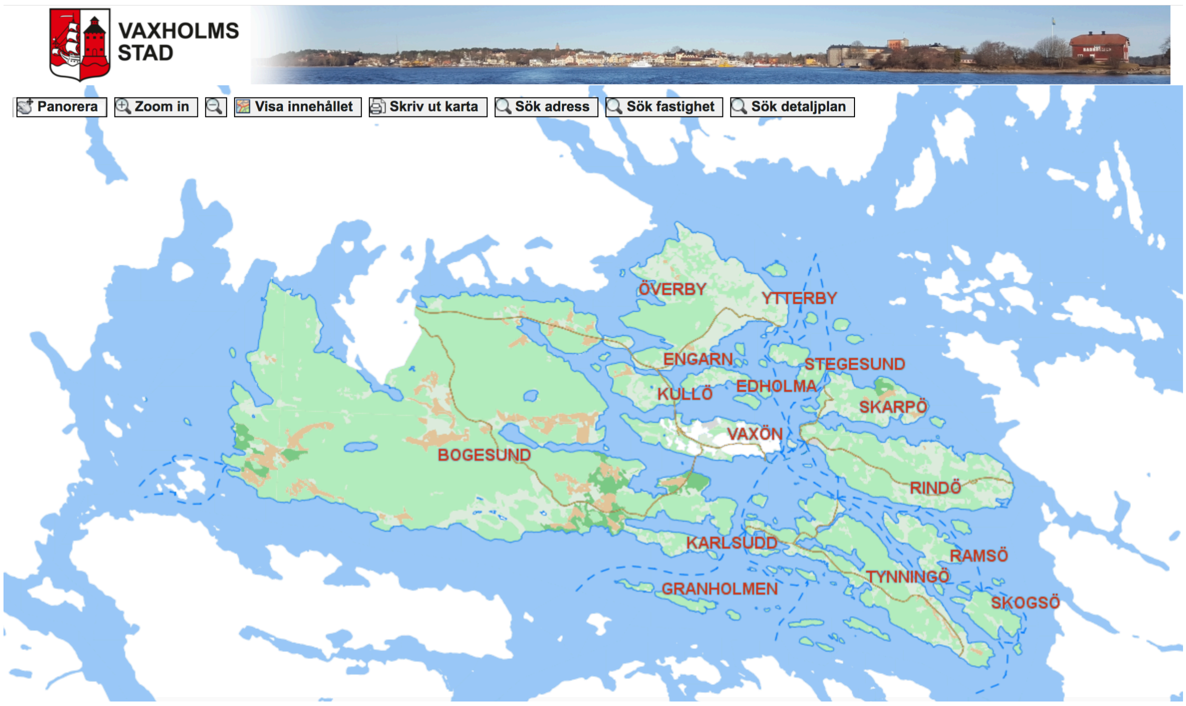

Figure 22: Extension of the municipality of Vaxholm (Vaxholms Stad, 2017).

Vaxholm features built-up areas of different density, indeed, besides Vaxön, the rest of the islands of the archipelago are not really populated. Also, the municipality presents extended green areas, water bodies and, despite there are still many well-preserved wooden houses from the last century, in the physical aspect it is a homogeneous municipality, which makes it suitable for the realization of the 3D city model.

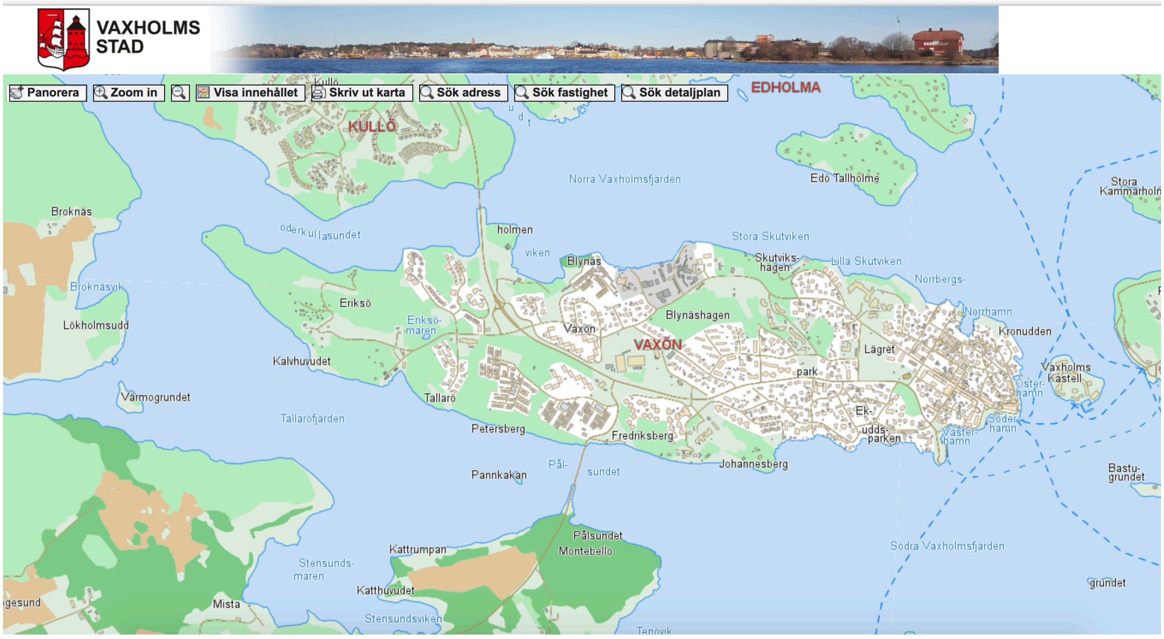

Figure 23: Extension of the island of Vaxön (Vaxholms Stad, 2017).

3.2 *From an academic internship to a master thesis project*

The aim of an academic internship is allowing students to take part in activities with a high professional content, working for private firms or, as in my case, for a public administration that works in the field of spatial planning and urban design. Additionally, during the development of this work experience, the student is supposed to be supported by the supervision of a tutor of the host institution, to be led by an expert and gain as much knowledge as possible in a short period of time.

In line with these goals, the project that I have developed together with the oversight of an employee at Vaxholms Stad, aims to create a system that allows 3D visualizations of Vaxön's urban structure since it is the main and most populated island of the whole municipality. Through the use of the software FME, and the combination of different data formats, such as LIDAR point clouds, 2D footprints in shapefiles and ortho images in ECW[6] (Enhanced Compression Wavelet), a geo database handled in a FME workspace has been created to represent and manage virtual 3D building models in LoD2 of Vaxholm. Lately, the content of the database has been exported in KML, the format supported by Google Earth, to allow citizens to easily read and view the 3D model in a free widespread used web-based mapping application as Google Earth. Moreover, by virtue of the multiplicity of transformers that FME has, a further characteristic added to the workspace assembled was the possibility to periodically edit and upgrade the data contents and also to transform the 3D model in different formats, *e.g.,* 3D PDF, COLLADA (COLLAborative Design Activity) and hence, to be read by a broad range of applications, such as ArcGIS, Web GL- based Cesium Virtual Globe and many others. Furthermore, *Detaljplaner* (Detailed plans) and *Projekt* (Projects) *pågående planarbeten* (ongoing plan work) are part of the model, represented as a zoning spread in the island of Vaxön in the proximity of those buildings that are part of the plans linked. Therefore, adding these plans has improved the usability of the 3D model as, not only a mere 3D visualization of the municipality, but rather as an effective urban planning tool. Indeed, these types of plans are legally binding and thus, considered as the most incisive ones at the

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[6] ECW: "These files are compressed images that typically store aerial and satellite map projections. ECW files can achieve compression rates between 1:10 and 1:100, making them ideal for compressing large images. Applications that support the ECW file extension for images include Adobe Photoshop 4.0 and 7.0, AutoCAD, Bentley MicroStation, FME, ArcGIS, and others. Retrieved on http://whatis.techtarget.com/fileformat/ECW-Compressed-image-files-for-aerial-and-satellite-map-projections

local level in Sweden. They are planned for specific areas of the municipality where particular development process makes such plans fundamental. For instance, they can be adopted for: new buildings of an urban settlement; evaluation of the potential development in an urban area; identifying a building with significant impact on the surrounding area and others cases (Solly, 2013). As aforementioned, only the plans where the planning process is still ongoing have been selected and added into the 3D model. Therefore, during the *iter* of approval, the municipality of Vaxholm could take into consideration different alternatives proposed by the citizens about those plans. Additionally, in Google Earth, these plans present an URL link in the attributes content that from a GE's window connects them directly to the plan information published on Vaxholm municipality's webpage. In this way, citizens have the possibility not only to inspect the 3D city model of Vaxön on a GE but also to have access directly from the model, specifically on the interested area, to all the detailed information about a certain plan/project and also about their current *iter* of approval, which are both already published on the Vaxholm's page. Also, thanks to Google Earth functions, each citizen can leave a feedback by e-mail to the city administration claiming either for their needs about a specific plan or only with their point of views about what has been mapped on the 3D model. For instance, providing some alternatives to the municipality administration about a certain plan, before its approval. Therefore, to let citizens easily have access to the 3D city model generated, the former will be subsequently published on Vaxholm's webpage, where the model is divided in eighteen sections, as it is shown below in figure 24, where each of them represents a KML model, *i.g.*, an area of the territory of Vaxön.

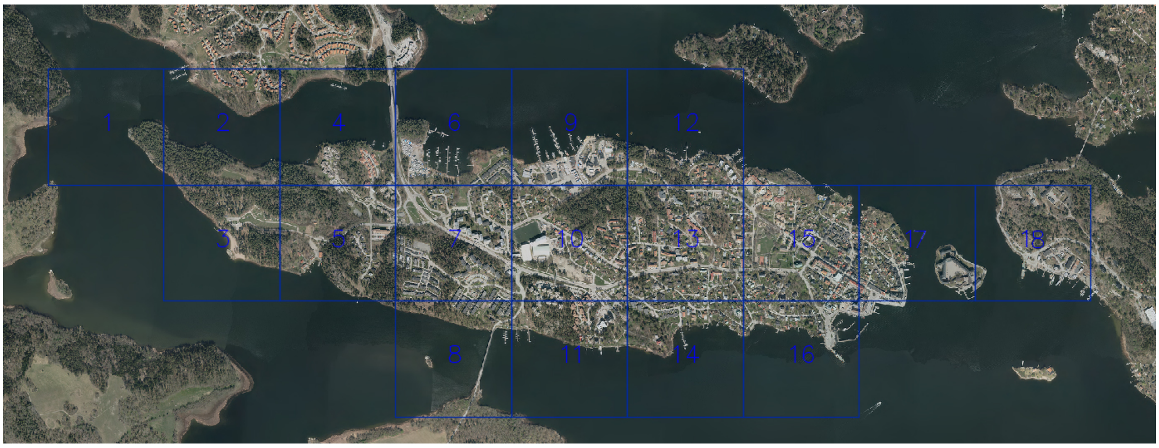

Figure 24: Eighteen sections divide the island of Vaxön. Each section represents a KML model (Own elaboration)

The main reason why the island have been splitted in several sections is that the LAS files, of which the municipality of Vaxholm is provided, are divided in sections too, hence we had to generate as much models as the number of LAS files that covered the territory of Vaxön. Furthermore, creating 3D models in smaller sections has allowed working with lighter files and thus, a faster and less complicated generation process of the KML models.

The model can be seen either using a single section, in case the user is interested only in a specific area, or even with all the sections together in a unique visualization through Google Earth. Therefore, since the areas correspond to the KML models, they can be easily switched on and switched off, as it is shown below on the left side in figure 25, according to users needs.

Figure 25: Visualization of the 3D buildings model on Google Earth. The sections on the left can be switched on and switched off according to users needs (Own elaboration).

3.3 *Creation of the workspace to generate a 3D buildings model*

Throughout the next paragraphs will be presented the workflow generated to reconstruct a 3D building model with textured roofs at LoD2 from existing two-dimensional data, of which the municipality of Vaxholm was already provided. Specifically, building footprints in shapefile, point clouds in LAS, and ortho images in ECW for the roofs texture have been combined to shape the 3D models. Lately, each model has been exported in KML format and then uploaded into Google Earth.

3.3.1 Reading data source

The datasets to generate the 3D building models have been created using basically three ‘ingredients’. As it is shown below in the figure 26, they are respectively the point clouds, an orthophoto and the building footprints, without any elevation attached to them.

Figure 26: Reader files employed to generate 3D buildings models: pointclouds, orthophoto, footprints (Own elaboration from FME Data Inspector).

However, since the aim was to create three-dimensional blocks out of building footprints, iw was necessary knowing the buildings elevations. Hence, the coordinate *z* has been extracted from the point clouds and assigned to the buildings shapefile. To do that, in a workspace have been imported two features types, *i.g.,* the readers that will read the data: the building footprints coming from an ESRI shapefile and the point clouds that come from a LAS file. The main features of the LAS point clouds, acquired by experts, employees of Vaxholms Stad, and used to shape the 3D models are: TopEye MKIII as lasersystem; a flight altitude of 450 m; a laser frequency of 70000 Hz.; the points density of 12 pkt/m^2; Therefore they were in appropriate scale and sufficient detail.

3.3.2 *Generation of a shapefile with elevations*

As it is shown below in figure 27, to extract the elevations from the point clouds the *Counter* has been connected to the footprints. This transformer, counting the features, adds a numeric attribute to them and creates a unique ID for each building.

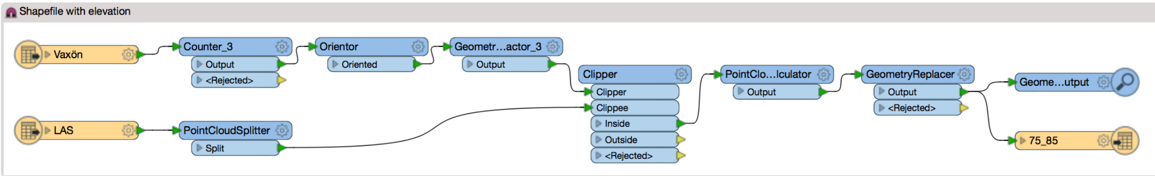

Figure 27: Workspace assembled to create a shapefile with elevations extracted from LAS file (Own elaboration from FMEDesktop).

Successively, once the *GeometryExtractor* have extracted the buildings geometry from the shapefile, and the *PointCloudSplitter,* connected to the LAS, have split out them to only get the last return, they have been both connected to the *Clipper,* which has clipped each point cloud keeping only those that were above the buildings surface, in order to extract the elevations (*z*) and thus, assigning them to the buildings, as it is shown below in the figure 28.

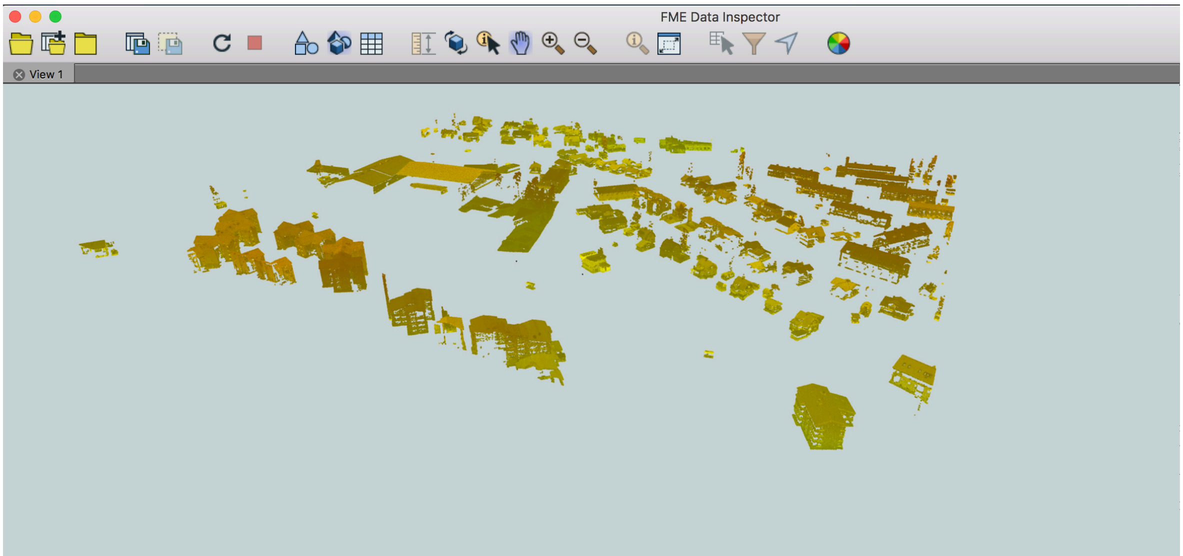

Figure 28: Workspace assembled to extrude the 3D building blocks out of the footprints shapefile (Own elaboration).

Lately, thanks to the *PointCloudStatisticsCalculator,* it has been possible extracting the median and the minimum value for each point cloud (shown below in figure 29) that represented the building's height at the roof top and the building's height at eave's elevation respectively. Hence, the *GeometryReplacer* has been used to restore point clouds with the buildings geometry and, lately, convert them, thanks to a *Writer,* in a new shapefile that after having used diverse transformers, presented the buildings elevations in its attribute table.

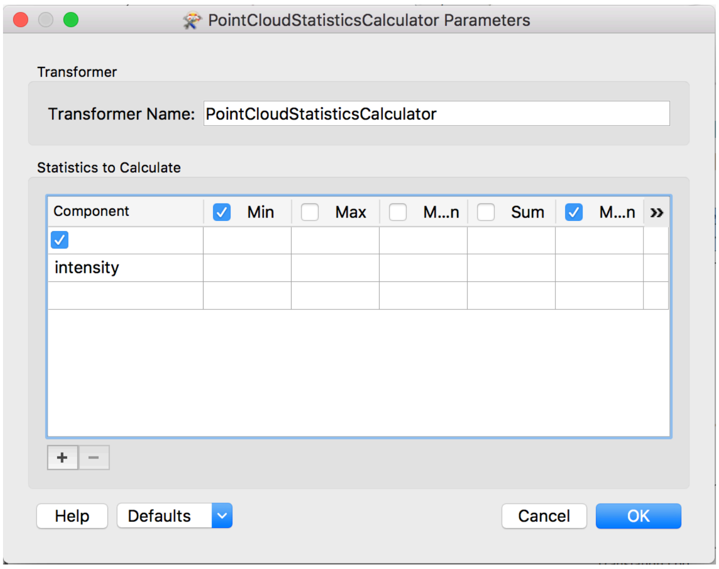

Figure 29: *PointCloudStatisticsCalculator* properties (from FME Desktop)

3.3.3 Extrusion of 3D building blocks

Once the shapefile containing the buildings heights attribute has been created, in another workspace, the building blocks have been extruded, according to the elevation values. In the figure 30 are shown the different transformers used to create the 3D blocks of the buildings.

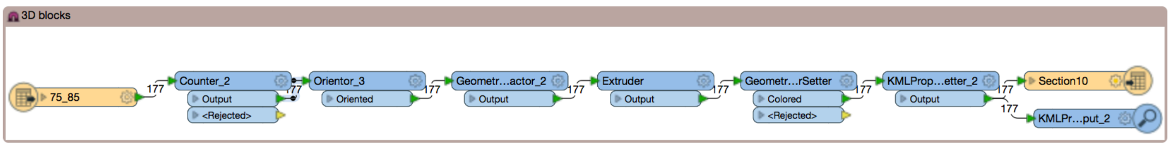

Figure 30: Path assembled to extrude 3D blocks (Own elaboration from FME Desktop)

Firstly, the shapefile has been connected to a *Counter* and then to a *GeometryExtractor,* where the same process, aforementioned, has been carried out within both transformers. The next transformer, *Extruder*, has been used to extrude the buildings blocks out of the footprints.

Thus, as it is shown in the next page in the figure 31, it has been set the extrusion input by *Height* and then selected the attribute *z_min* of the shapefile as the elevation for the blocks extrusion at the eave's elevation.

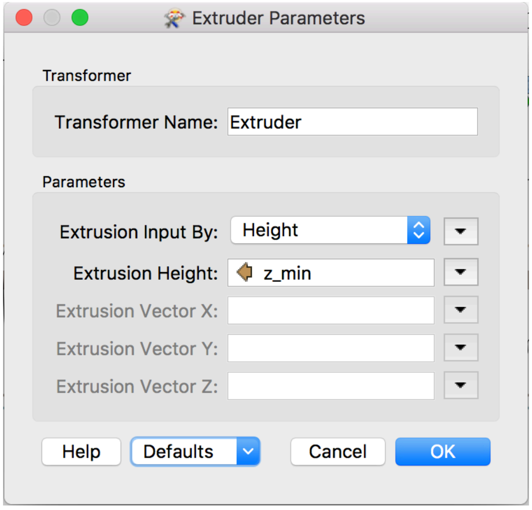

Figure 31: *Extruder* parameters (From FMEDesktop)

Lastly, the *GeometryColorSetter* can be optionally used to set a desired color for the 3D blocks and the *KMLPropertySetter* has been used, before converting the models in KML format, to specify the altitude mode that the model will have when loaded in Google Earth. In this case it has been set *Clamp to the Ground* and then the model converted in KML through a GoogleKML *Writer*, where the Swedish coordinate system SWEREF-99-18-00 has been set to the model.

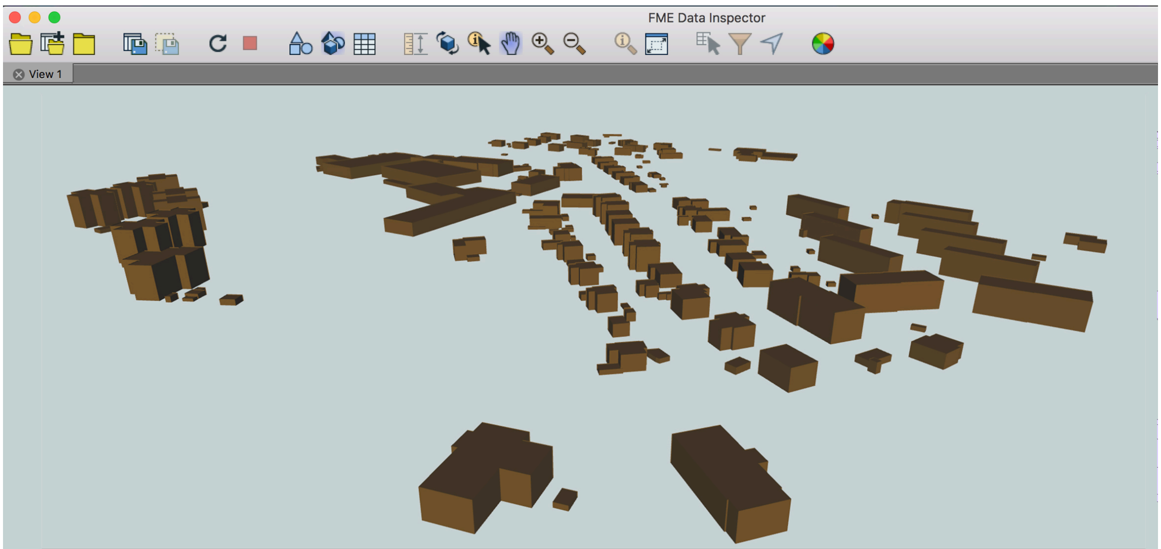

Figure 32: 3D building blocks (Own elaboration from FMEDataInspector)

In the last page in figure 32 is shown how the building blocks look in the FME Data Inspector after the extrusion, still without roofs surface.

3.3.4 Creation of a roof surface

Successively, aiming to create a LoD2 3D model, *i.g.,* buildings with differentiated roof structures, another workspace has been assembled as it is shown below in figure 33.

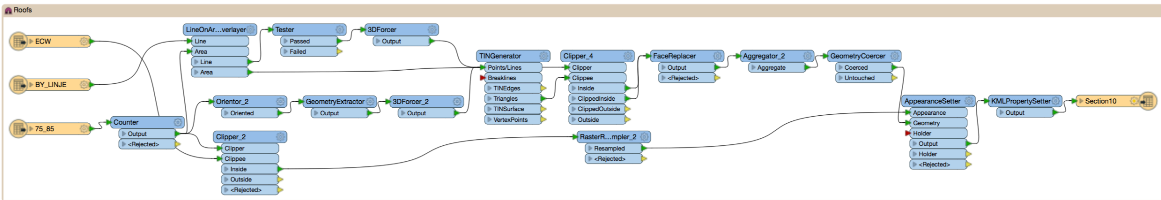

Figure 33: Workspace to generate building roofs with real textures (Own elaboration from FMEDesktop)

The first transformers have been used between the buildings shapefile with heights attribute and a DWG file, which contains median lines that correspond to the top of the roofs, used as readers. Since the models were divided in sections and in each section the number of buildings was not very copious, it has been easily extracted a median line from each roof of ridge lines in Vaxön, using the AutoCAD tool, *DRAWBUILDSYMBOL*, which generates these lines out of the DWG footprints as it is shown below in figure 34.

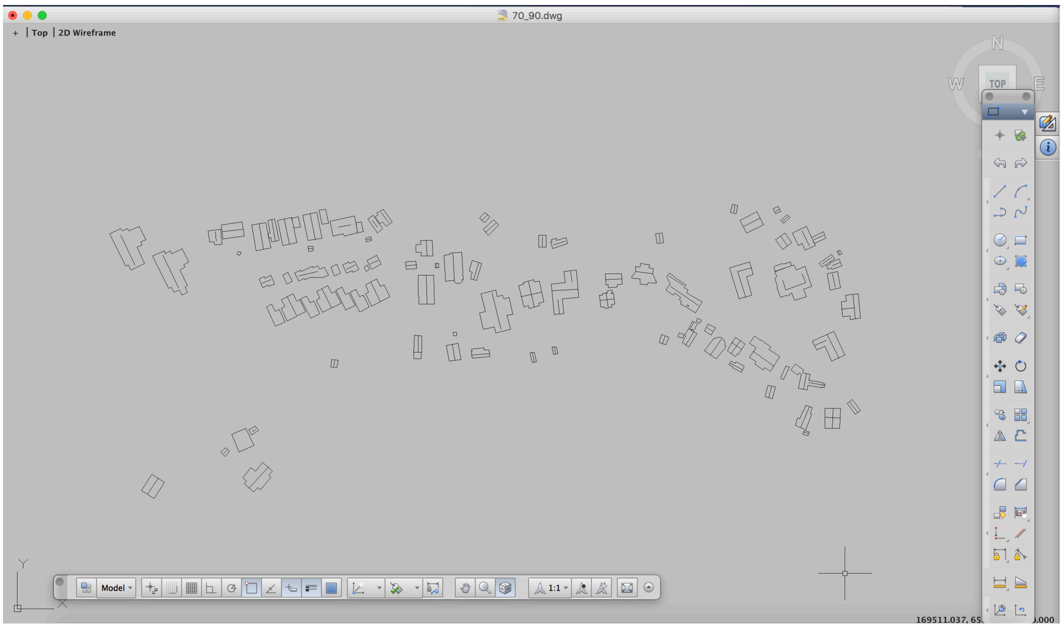

Figure 34: Centerlines of roofs in DWG file (Own elaboration from AutoCAD).

As it is shown in the zoom below (figure 35), the transformer *LineOnAreaOverlayer* has been employed to transfer attributes, in this case the heights, from buildings to the centerlines of the roofs and then the *3DForcer* to force those lines to the heights of the roof tops (*z_median*). In the meanwhile, the buildings shapefile with a different path has been extruded to the heights of the roof's eaves (*z_min*), with exactly the same procedure and the same heights used in the previous workspace (*Counter-Orientor-GeometryExtractor-Extruder*). Successively, the footprints and polylines respectively at their heights have been both connected to the *TINGenerator* transformer, which, using them as benchmarks, has generated a triangle surface for each roof, shaping pitched roofs.

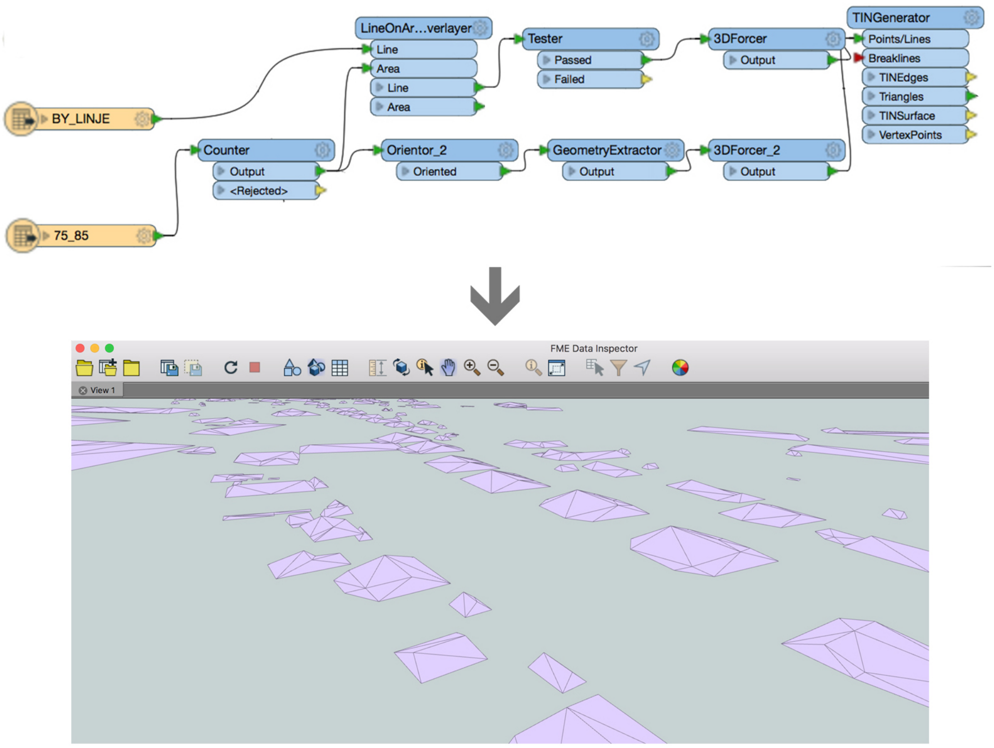

Figure 35: **On the top:**Workspace to generate triangles for roofs surface. On the bottom: roofs visualization (Own elaboration in FMEDesktop and in FME Data Inspector).

Additionally, a further step that has been made before creating a roof's surface was verifying if each building had, in the reality, a flat roof or a pitched one. To do that, a Blom oblique aerial imagery has been employed, which is an integrated service that from a pushbutton on Vaxholm's web-GIS connects, remotely, to the Blom, referred to Vaxholm's area only. This oblique image, taken with an angle of approximately 45°, has allowed visualizing the facades of the buildings and hence, also to recognize if a roof was flat or not.

As it has been mentioned throughout the last chapter, geo-referenced oblique imagery usually extends the benefits of traditional vertical aerial imagery, providing a perspective view of certain buildings and areas, in order to allow users identifying peculiar features that would be difficult distinguishing on traditional vertical imagery (BlomASA, 2017). Therefore, thanks to the Blom oblique image, of which the municipality of Vaxholm was already provided, when a roof was recognized flat, for instance, the roof of a garage, the centerline created in AutoCAD for that building has been erased from the DWG file and thus, there was not any benchmark above certain buildings to generate the surface.

Furthermore, besides the identification of the flat roofs, the Blom oblique image, thanks to some tools, had the ability to measure the heights and lengths of the buildings directly from imagery and hence, the attributes contained in the files created have been compared and then verified if they were correct or not. In the figure 36 below is shown a zoom of the island of Vaxön visualized in Blom oblique image.

Figure 36: Blom aerial oblique image, visualized throguh Vaxholm's web-GIS (Vaxholms Stad, 2017).

However, through this process, it has not been used the real roof structures for all the buildings, instead, has been applied a simple centerline extraction, which mostly works quite well, but in some cases, it creates lines that do not look correct, and this is more visible when the orthophoto is textured on the roofs, when in some faces of the surface the image does not appear at all.

3.3.5 *Real textures for buildings roof*

After having created the roof's surface with triangle faces, these triangles have been clipped with the buildings footprint using the *Clipper,* a transformer that has allowed to create a boundary cutting the triangles that went outside of the footprints. Then, through the transformers *FaceReplacer, Aggregator* and *GeometryCoercer,* respectively, it has been extracted faces from the polygons (created with the *TINGenerator* and then clipped), combined these geometries in homogeneous aggragates and generated an *fme_composite_surface* (selected in the *Geometry Type* of *Geometry Coercer* parameters). The figure 37 below shows the path followed to make the roofs surface.

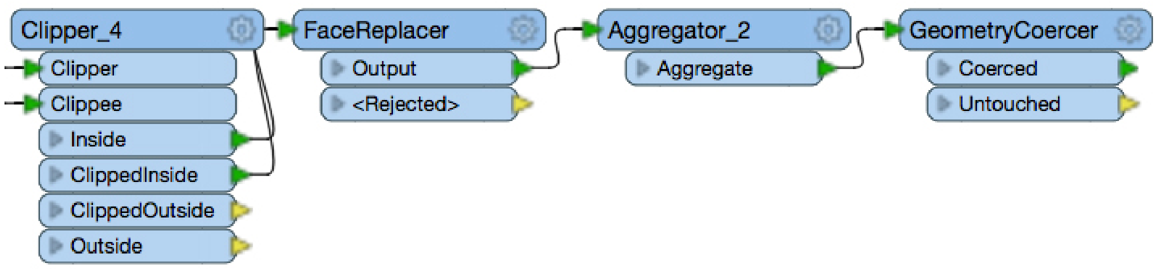

Figure 37: Path to make the triangles in composite surfaces (Own elaboration from FMEDesktop)

Once the roofs surface have been shaped, the path to texture the orthophoto on the roof's surface has been developed, as it is shown below in figure 38.

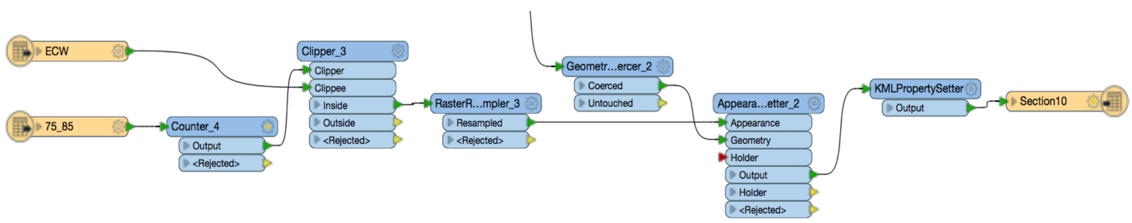

Figure 38: Workspace to texture the orthophoto on pitched roofs (Own elaboration from FMEDesktop).

In this case the readers employed were, again the buildings shapefile, and the orthophoto of Vaxön in ECW format. Firstly, after having used the *Counter* to add a numeric value to the buildings, the *Clipper* has been employed between the two readers aforementioned to keep only the raster that stands above the roofs and cut off the rest of it. Successively, to further simplify the raster size, it has been used the transformer *RasterResampler.* Therefore, at this stage, both the previously generated roofs surface and the just clipped and simplified raster have been connected to the transformer *AppearanceSetter,* which has been used to set an appearance style onto the front sides of roofs geometries. Indeed, thanks to this transformer, all the surfaces created could have the appearances set directly on them. Lately, the *KMLPropertySetter* has been used again in this workspace, before converting the models in KML format, to specify the altitude mode that each model needs when it will be loaded on Google Earth. Again, the model has been set *Clamp to the Ground* and then converted in KML through a GoogleKML *Writer*, where the Swedish coordinate system, SWEREF-99-18-00, has been set.

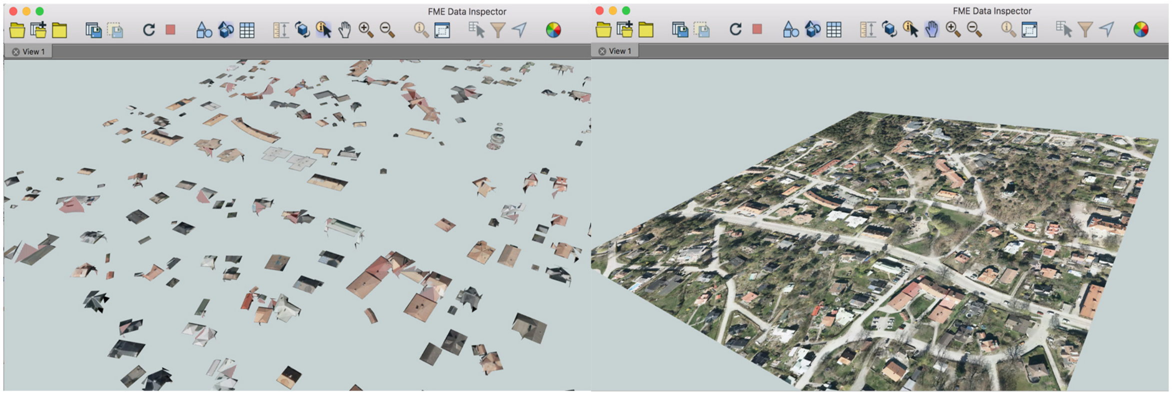

Figure 39: On the left: real textures on pitched roofs. On the right: the ECW clipped with the area of interest, which shows where the roofs textured are located (Own elaboration from FME Data Inspector).

In the figure 39 above it is shown how the textured roofs surface appear in the FME Data inspector.

3.3.6 Combination of the workspaces created

Throughout the last paragraphs, it has been assembled essentially three workspaces: the first might be considered as a pre-processing of data since it has been used to assign the elevations attribute from the LAS files to new shapefiles. Differently, both the second and the third workspace have in common the same goal, which is shaping 3D building models. However, they have been used to generate two different components of the 3D models, following two different paths that involve different combination on transformers. Indeed, the first has been employed to extrude the building blocks and the second one to create pitched roofs with real textures. Therefore, since the two workspaces can be considered as part of the same process, they have been combined together within the same bookmark to shape integrated 3D building models, as it is shown in the next page in figure 40.

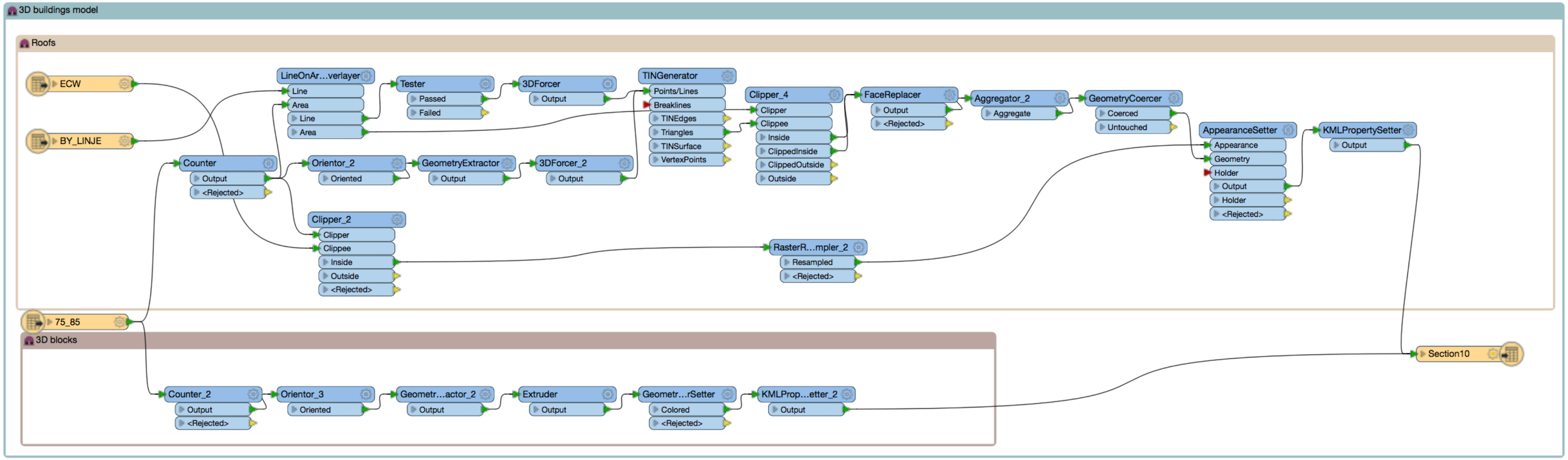

Figure 40: Workspace assembled to shape integrated 3D buildings models (Own elaboration from FMEDesktop)

In this way, inside the bigger bookmark, called *3D buildings model,* there were the two smaller bookmarks described in the last paragraphs, the *3D blocks* and the *Roofs*. These workspaces have in common, in the beginning a *Reader*, which is the shapefile with the elevations attribute, and at the end a *Writer*, which has been employed to combine together the 3D blocks generated throughout the first workspace with the respectively textured roofs created in the second one. Lately, yet with the same *Writer* the 3D buildings assembled have been converted in a unique KML file that have been uploaded and visualized in Google Earth.

As aforesaid, the 3D models generated have been split in several sections due to the LAS files structure. Hence, the same workspace aforementioned, which combines different paths to generate different components within itself, has been repeated eighteen times with different LAS files to create eighteen different KML models. As it is shown below in figure 41, the KML 3D models have been positioned in the environment of Google Earth, which presents as in the reality the slopes of the earth according to the sea level and thus, providing a real atmosphere to the surrounding areas of the buildings, has allowed the correct position of the 3D buildings.

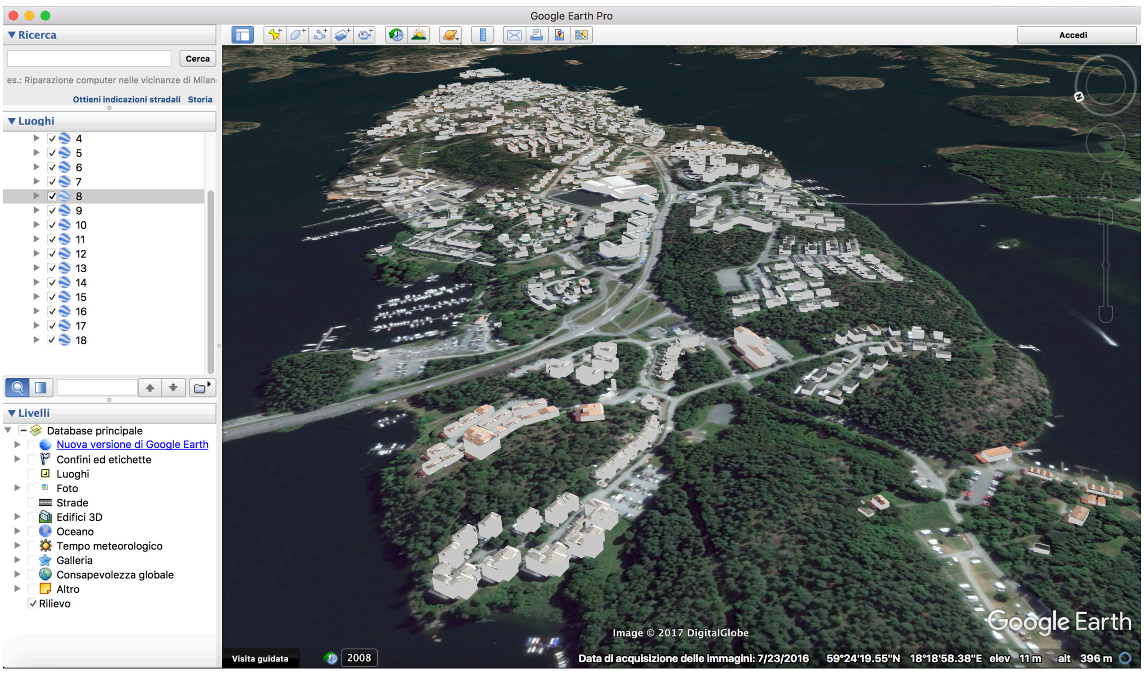

Figure 41: KML 3D buildings models uploaded on Google Earth (Own elaboration on GE).

3.3.7 *Detailed plans and Projects*

Fundamental components of the 3D building models are the Detailed plans and Projects, which have been loaded and depicted as a zoning on Google Earth in proximity of those buildings that concern a certain plan. As aforesaid, these types of plans are quite significant at the local level since they are legally binding and thus, considered as the most incisive ones to manage, for instance, the construction of a new building, which may have a significant impact on its surrounding area.

Therefore, several plans for detailed planning of Vaxön with still an ongoing plan work, as it is shown below in figure 42, have been selected from the municipality's website, and successively, integrated with the 3D building models created.

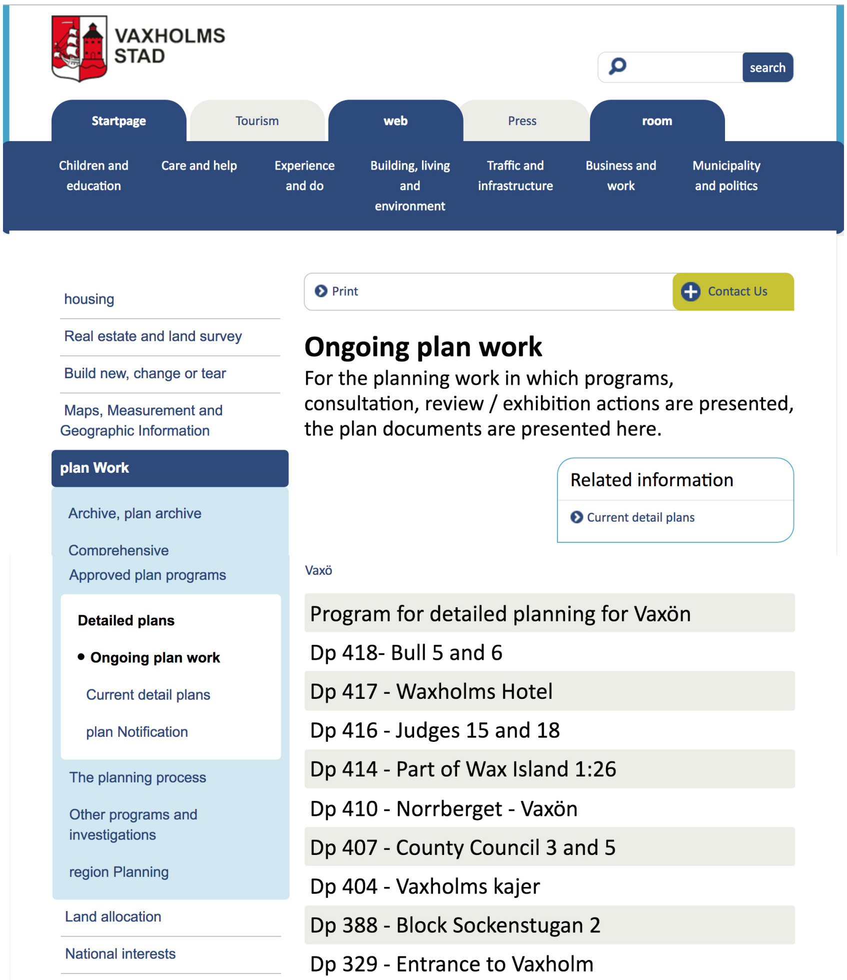

Figure 42: List of detailed plans and projects still in pending approval published on Vaxholm municipality's webpage (Vaxholms Stad, 2017).

The choice of integrating with the 3D building models only the plans where the planning process is still ongoing, has been made because, on the one hand, throughout the *iter* of approval of these plans the citizens would still have the possibility to refer to the interactive model to express their opinions or likely complains about the plans, and on the other hand, the municipality of Vaxholm would be able to take into consideration different alternatives proposed by the citizens about those plans before their approval.

Therefore, the shapefiles containing the perimeters of these plans have been edited adding, in both of them, a new field in the attribute table with a specific URL link for each plan. Moreover, in the attribute table has been specified for each plan the unique code and the name of the plan, exactly how they look on Vaxholm municipality's website, as it is shown below in figure 43. The URLs will be visible in several clickable pop-up windows on Google Earth and will connect the plan's perimeters directly to all the documents, but also to their current *iter* of approval, which are both already published on Vaxholm municipality's webpage.

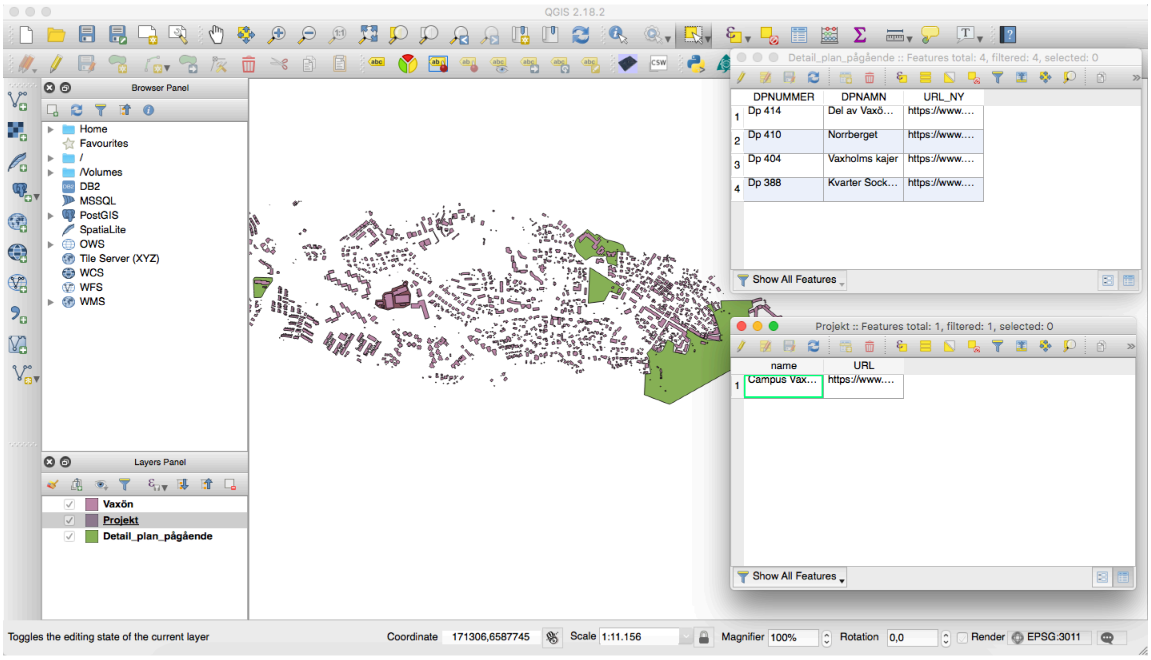

Figure 43: New fields in the attribute table of both detailed plans and project shapefile, containing a URL link (Own elaboration on QGIS).

Successively, these shapefiles have been imported in a new workspace on FME and, with the employment of two transformers, converted in KML format. As it is shown in the next page in figure 44, both the *Detaljplaner* and the *Projekt pågående planarbeten* have been connected, firstly, to the *KMLStyler* to set a specific color for their visualization on Google Earth, and then, to a *KMLPropertySetter,* giving them the same properties that have been given to 3D building models before converting them in KML format, *i.g., Clamp to the Ground.* Lately they have been both connected to a GoogleKML *Writer,* to convert them in the format supported by GE and providing them the right coordinate Swedish system, SWEREF-99-18-00.

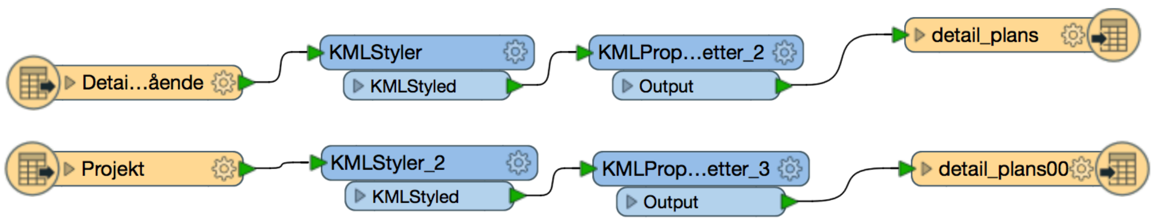

Figure 44: Paths to generate KML files, which contain detailed plans and projects (Own elaboration from FMEDesktop)

3.3.8 *Results achieved*

Once converted in KML format, the files created with FME (Detailed plans and Projects) have been uploaded and visualized together the eighteen sections (3D building models) previously created and displayed in a unique visualization on Google Earth. In this way the plans have been clamped to the ground, using the proper transformer on FME, corresponding to specific areas and buildings (the yellow and the blue areas in figure 45 below).

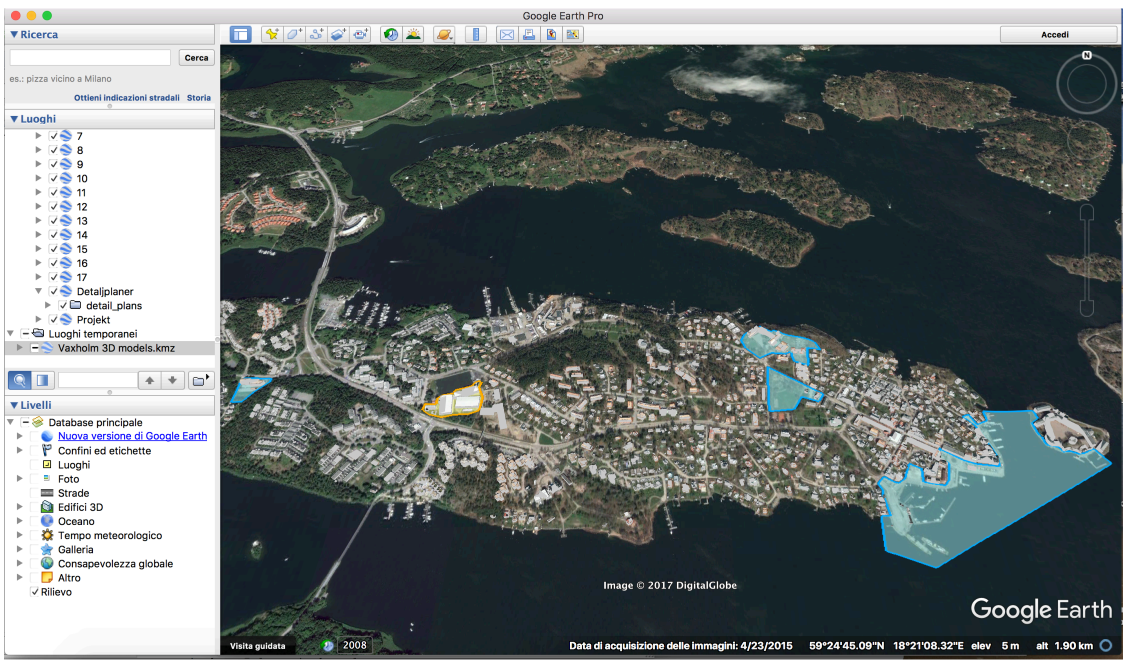

Figure 45: Visualization on Google Earth of the 3D models, detailed plans and projects (Own elaboration from GE).

At the same way of the other sections, the plans mapped on GE can be easily switched on and switched off from the legend on the left side, according to the users interest, and also since they are clickable, in a pop-up window the URL link connect them to the webpage of the municipality. For instance, below in figure 46, the URL with a code name *Dp 410* connects to its info-page, Detailed plan for the area of Norrberget, published on Vaxholm's website.

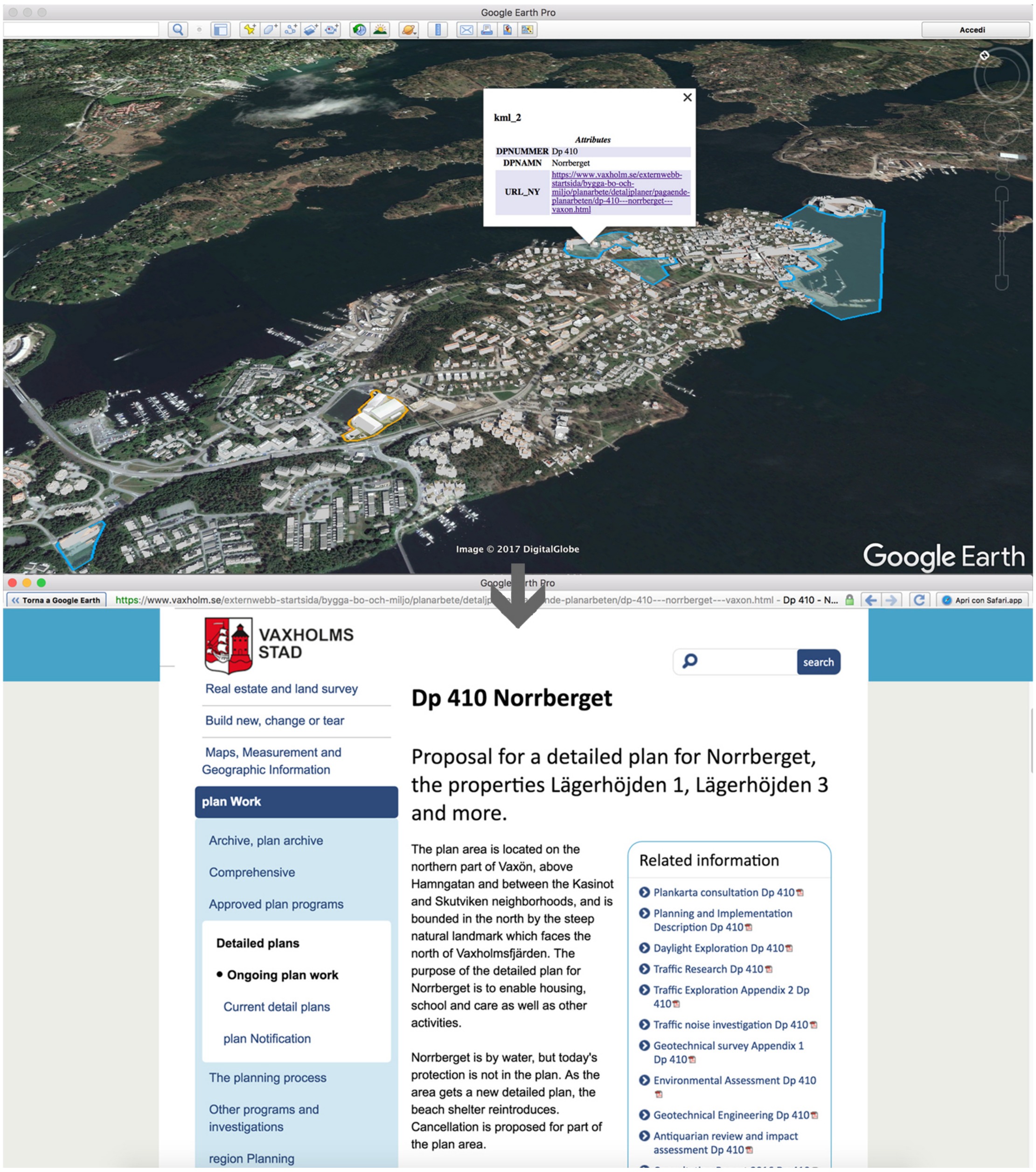

Figure 46: On the top: the pop-up window cointaining a URL link (Own elaboration from GE), which connects directy to the detailed plan information on the municipality's website (On the bottom).

In this way each citizen can easily have access to all the information related to a certain plan. For instance, as it is below in figure 47, a vertical view of the area of Norrberget is one of the document available on the Dp 104 page, which shows the perimeter of the Detailed plan of Norrbertget. The purpose of the plan for this area is to enable housing, a new school as well as other activities connected to the former, spread in the area.

Figure 47: Area of the Detailed plan of Norrberget. Figure from Planning and Implementation description document (Vaxholms Stad, 2017).

From the same webpage of the Detailed plan, citizens can also have access to a description about events from the past that have characterized this area, called 'Background' in figure 48 in the next page, and thus, it has been justified what has led the municipality to draw up a plan in a certain environment.

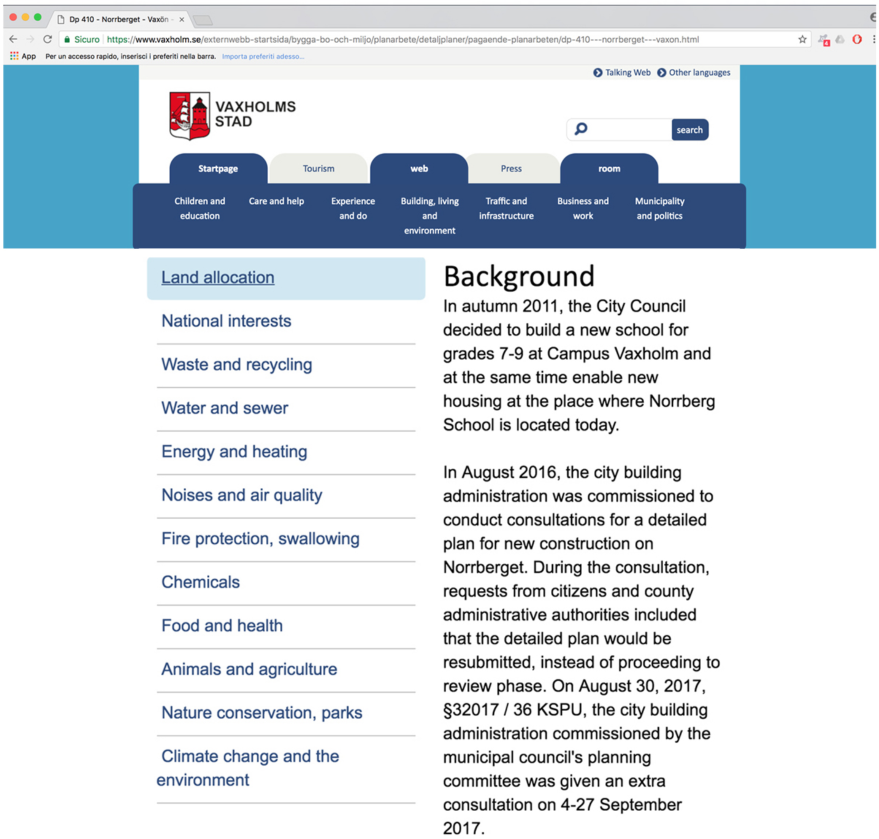

Figure 48: Description of the past events that have carachterized the area of Norrberget (Vaxholms Stad, 2017)

Furthermore, citizens, scrolling down the page, can inspect the various phases of the planning process of the Detailed plan of Norrberget, where the phases that the plan has already faced in the past are described and present a certain date set, as it is shown in the next page in figure 49, and on the other hands, those ones that the Detailed plan will face in the next years before its approval will be successively posted in the municipality webpage.

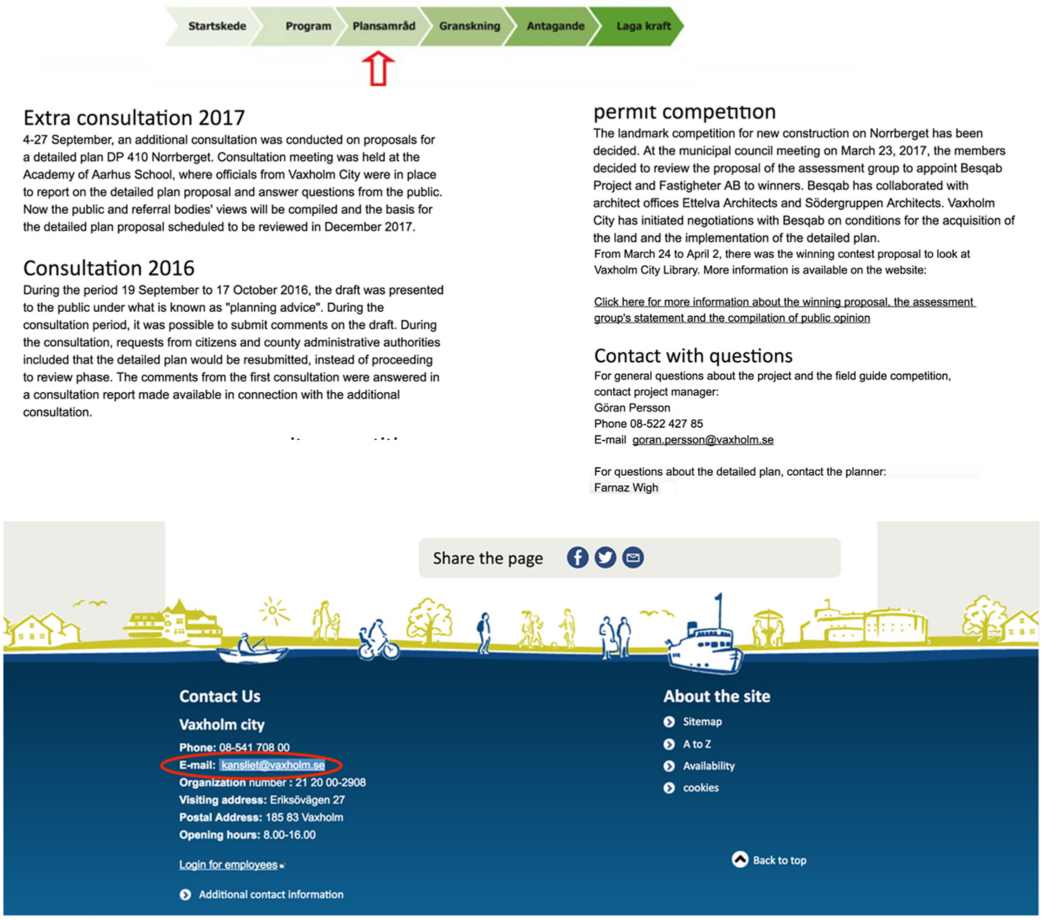

Figure 49: Iter of approval of Norrberget's detailed plan (Vaxholms Stad, 2017).

Additionally, for each plan, all the documents about prior analysis and studies, *e.g.*, traffic, social and demographic, conducted before drawing up the plan, planimetries and several maps containing measures and quantities about the construction of new buildings and any other information about the area of interest, are available published on the webpage. For instance, in figure 50 in the next page, is shown an aerial map (*Plankarta samråd*) part of the Detailed plan, which shows how the intended uses of the area would look like if the plan will be approved.

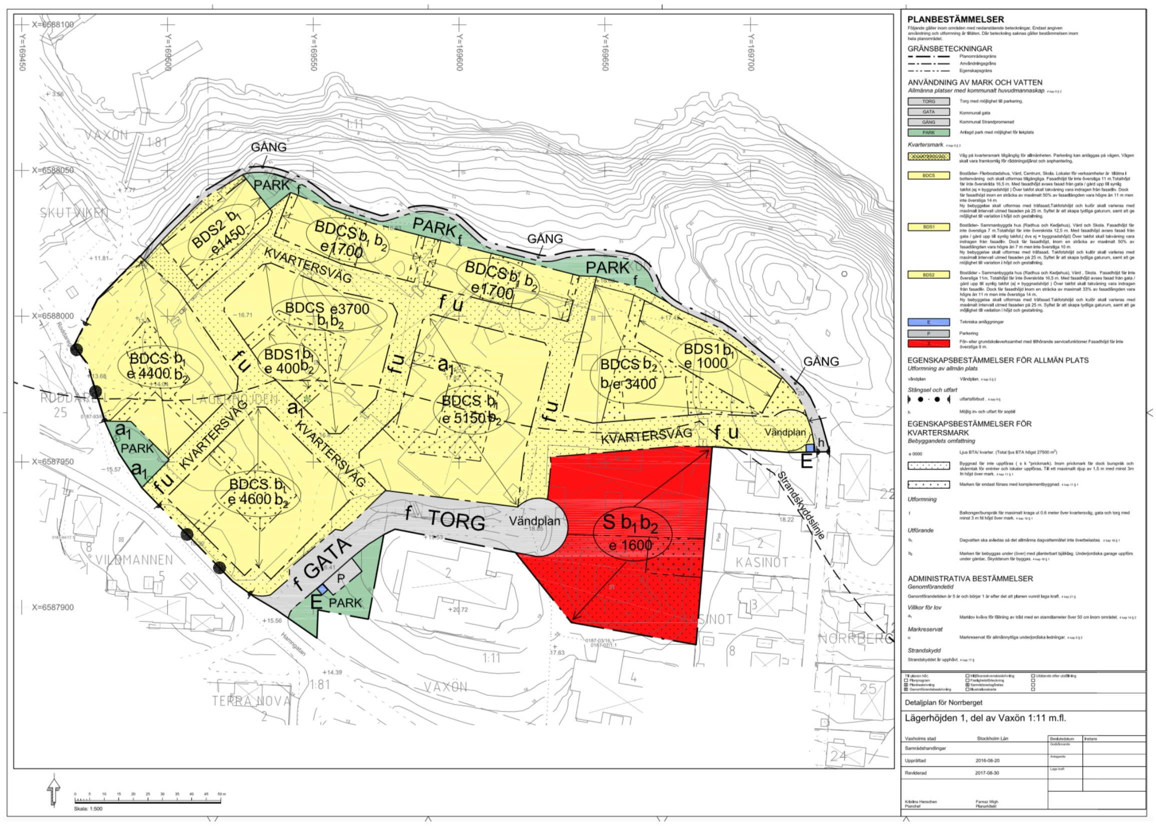

Figure 50: *Plankarta* of Norrberget's detailed plan (Vaxholms Stad, 2017).

In the light of that, the integration between the 3D building models and the plans with pending approval may represent a helpful planning tool for those citizens who are not familiar with a web-GIS portal. For this reason, a free widespread program with an easy interface as Google Earth, has been chosen for the visualization of an interactive 3D building model.

Furthermore, the inhabitants of Vaxholm, besides the visualization of the 3D models and the connection that detailed plans and projects have with the municipality's webpage, thanks to a Google Earth's functions, have also the possibility to login in GE with their private e-mail account, as it is shown in the next page in figure 51, and leave either their negative or positive feedbacks sending an email to Vaxholm city at kansliet@vaxholm.se (shown previously on the bottom side of figure 35). Indeed, as it is shown in the next page in figure 38, they can zoom on the area of interest and then select the command 'e-mail' on the top choosing which option they prefer among a screenshot, a KML that opens the current view in GE, or a KMZ that opens a placemark in GE. The three options are shown respectively in figure 52, 53 and 54.

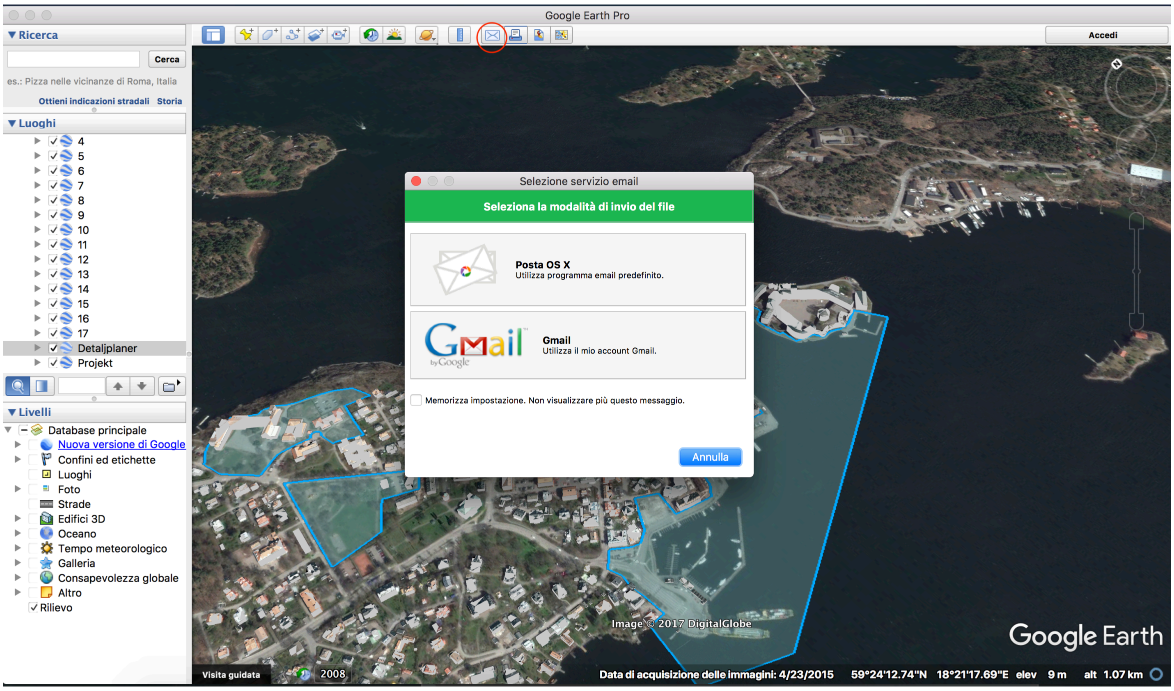

Figure 51: Login page on Google Earth to let citizens leave a feedback about a plan via email (Own elaboration from GE).

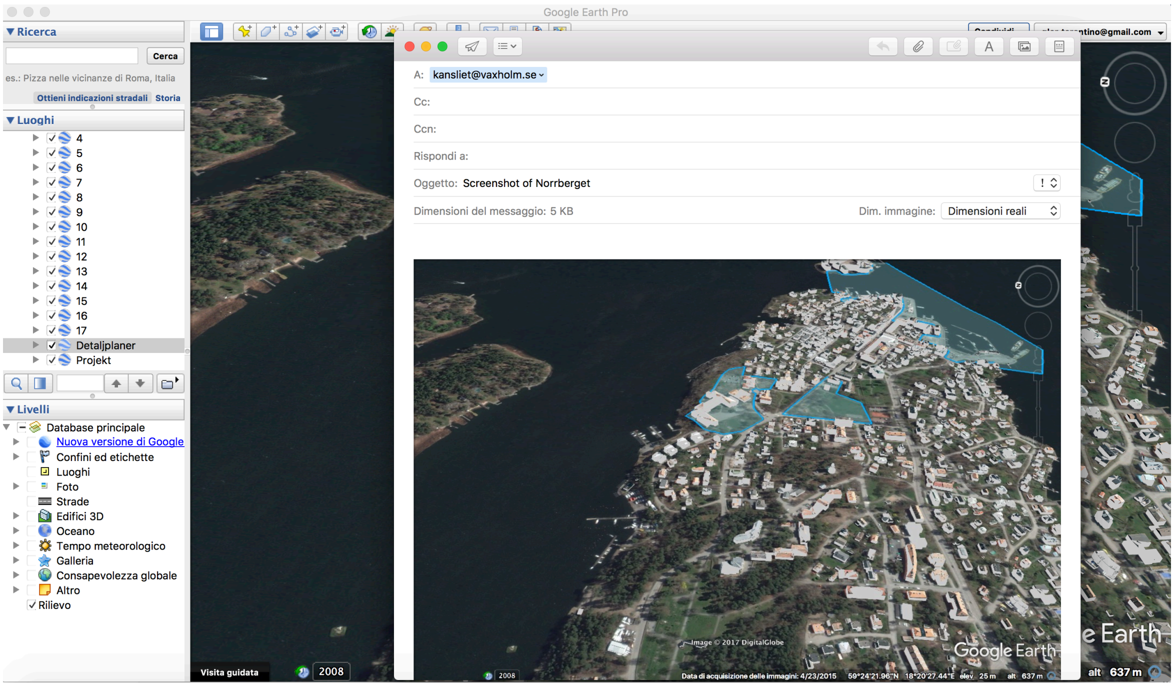

Figure 52: Email box page through Google Earh with a screenshot about the area of interest (Own elaboration from GE).

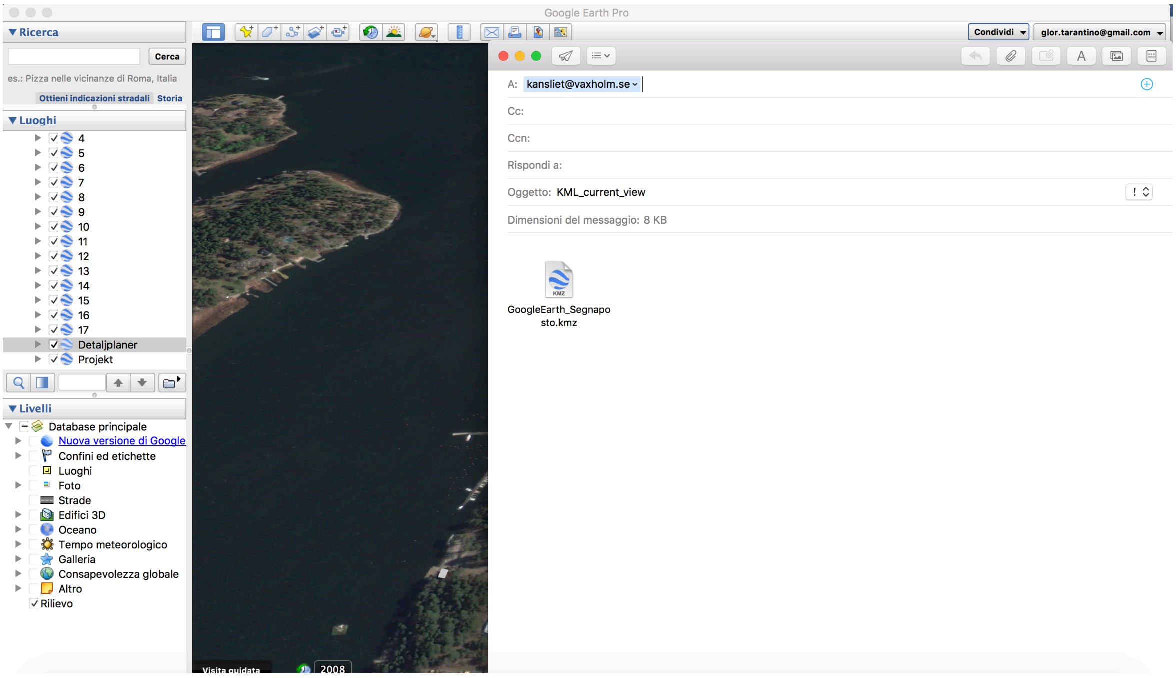

Figure 53: Email box page through Google Earth with a KML about the current view of area of interest. (Own elaboration from GE).

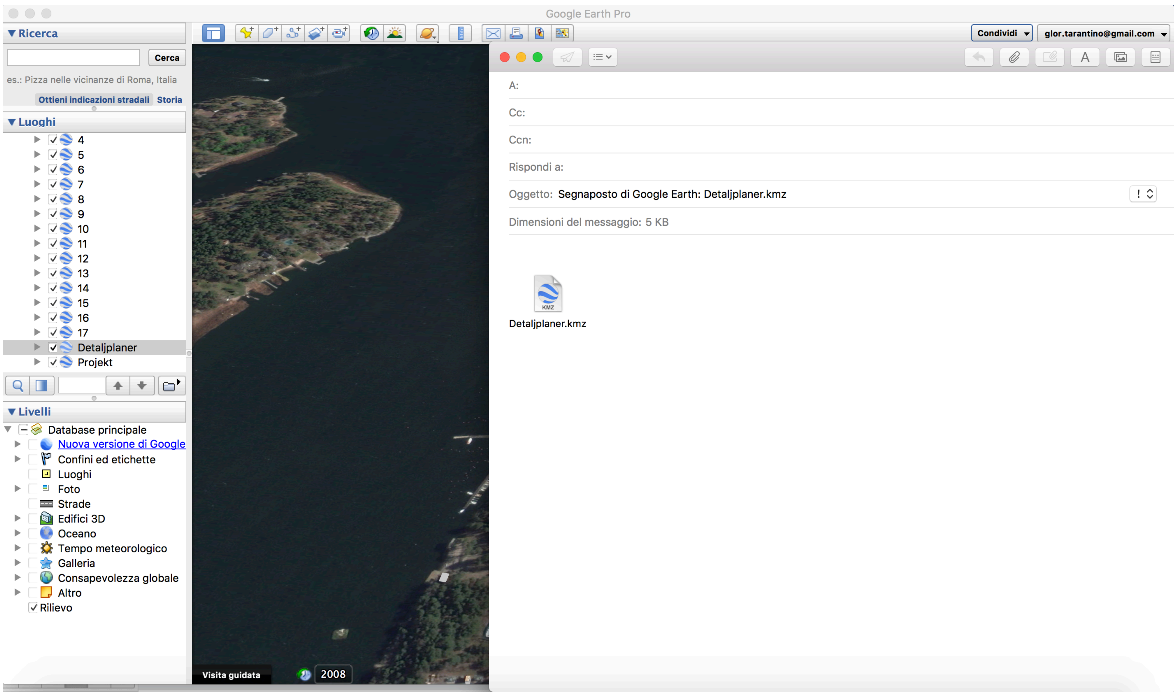

Figure 54: Email box page through Google Earh with a KMZ of the Detailed plan about the area of interest (Own elaboration from GE).

In this way each citizen is able to log-in on Google Earth with his private e-mail account and send to the municipality of Vaxholm his opinion, complains and proposals about a building or a whole area, in order to attach to the e-mail a screenshot or a KML about what the subject on which he is interested in. Therefore, Google Earth, besides a simple visualization of the 3D model generated, provides a user-friendly tool to the citizens of Vaxholm, which allows them to have a clear and quick access to all the information about what is going to happen in certain areas, in order to give them a chance to have voice within the planning process of those plans with pending approval.

3.4 *Future applications and improvements*

Throughout the demonstration shown in the last paragraphs about extracting elevations from LIDAR point clouds, assigning them to new building footprints and from the former generating the 3D building models, which successively have been transformed to KML format for interaction and visualization in Google Earth, likely future improvements have been supposed as well as some limiting factors have emerged.

A limit factor that GE has shown in visual communication concerns when displaying or querying the 3D blocks. During this procedure is impossible accessing linked attribute about 3D solids by selecting anywhere on them. To overcome this lack, every building and, if the model would be a LoD3, even every single object of the 3D buildings should be decomposed into KML format as 3D polygons. In this way every component and sub-component of every building would be individually available for contextual querying. Indeed, this procedure, as shown in the last paragraph, works with the KML of the Detailed plans and Projects, which can be selected and their spatial and non-spatial properties accessed, but does not work with the others eighteen building models created, which instead contain numerous buildings within the same model. However, given the complexity of the 3D building models, especially if the buildings would be decomposed within the same KML model, the number of polygon vertices might not be supported by GE for a real-time display. Therefore, the complexity of the model in the KML models has to be reduced (Truong-Hong *et al.*, 2013).

The first step achieved regards the main purposes that have led the generation of a LoD2 3D building model of Vaxholm. These purposes were providing a three-dimensional visualization of the urban environment of the municipality through a popular online web mapping platform as Google Earth where the 'general' public could freely inspect and interact with the models retrieving specific information about buildings details, intended uses and contents of local plans. Additionally, as aforementioned, the employment of GE has provided a visual communication of planned development of Vaxholm and facilitated the engagement of the citizens, but also to every user interested, to take part to the planning process, and specifically to the *iter* of approval of the Detailed plans planned in Vaxholm.

In the light of that, with the employment of an user-oriented approach, the 3D city models created might be extended towards diverse applications and several improvements might implemented on them. A hypothetic tool to integrate the use of the 3D model in other tasks would be performing workshops with different stakeholders identifying also users needs. Thanks to workshops with the city administration, the departments of urban planning and facility management, and the citizens involved, fundamental information and different opinions about new tasks could be gathered, that on the one hand, have to be realizable in a context like this, and on the other hand, should have a value for the municipality of Vaxholm. The information collected by workshops and, if possible, interviews with experts, might provide more detailed information about the analysis of requirements needed for those tasks that represent a further support to the 3D building models generated, for instance, evaluation of the solar potential of rooftops, suitability of a roof surface for installing a photovoltaic panel above it or the assessment of energy demand of households. Once the information have been gathered and analyzed, can be also structured in a certain way, where specific task can be identified, described and assigned to a field of expertise (Albrecht & Moser, 2008). Lastly, it can be argued that performing surveys and utility workshops, the use of the 3D model generated can be enriched and extended to additional fields, identifying new tasks that result valuable for citizen needs and for the municipality of Vaxholm.

A further improvement to the 3D city models generated, regards the buildings reconstruction process. Indeed, the manual method adopted has shown to be time-consuming and totally dependent on operator's experience. Therefore, as the next step to achieve, a semi-automatic approach could be developed, for instance, focusing on reducing the post-processing time. Additionally, since GE is a free web-mapping platform with some limitations, and FME is a software able to export in several different formats, others more appropriate web platforms might be employed for the visualization of the model, trying to address the GE's restrictions, such as Microsoft Bing Maps, MapQuest, OpenStreetMap and many others.

Conclusion and final remarks

The evidence presented in this dissertation clearly indicates that 3D city models have proved to be estimable for a large number of domains during the last few years and thus, have been recently used in large number of application ambits and for diverse purposes related to cities development that, throughout this essay, have been classified according diverse criteria. These principles can regard the geometry of the building, if the task, for example, is the estimation of shadow; or semantic information stored in each building, if we refer to the estimation of solar irradiation. However, the most relevant criterion followed to individuate two main groups, concerns the visualization or non-visualization of 3D models. Indeed, besides being the first early-use domain of application for 3D city models, visualization is arguably an indivisible part of the workflows that involve 3D city models and it can be considered as the only criterion that is adaptable to almost all categories of applications mentioned in the last chapters.

Successively, in examining how the utilization of 3D city models in purposes related to urban analyses is growing, some interesting patterns have been delineated. For instance, it has been revealed that, by virtue of new technologies and methods for data acquisition and processing that have enhanced the efficiency of 3D city models, in order to make the whole process of the models generation less expansive and time-consuming, the requirements of 3D city models have changed direction: from a mere realistic geographical representation of cities that provides to users public access for the exploration of 3D elements, currently, the goals that a city administration wants to achieve using a 3D city model go towards the realization of a detailed and attractive representation of the urban environment that, thanks to specific interactive functions, enables users to retrieve from buildings, as well as from their sub-components, spatial and non-spatial attributes data when they interact with the model. As it has been shown in many cases of studies aforementioned, this information stored in the 3D model may regard the building features about its structure, both spatial and non-spatial (*e.g.*, height and number of households that live in the building), or on the other hand, may concern a future development plan drawn up for the area of interest that shows how the area would look like in the future, or as in the case of Vaxholm, the model visualized in a web-mapping platform can present some clickable pop-up windows that connect users directly to municipality's webpage where all the documents related to the plans of interest are published and open for inspection.

Another pattern emerged regards the recent increasing spread of 3D city models towards a larger number of public and private institutions such as, city administrations, mapping agencies, private firms, universities research departments and many others. Most of research papers and articles available on the web, documenting uses of 3D city models and integration of them as planning tools employed by several municipalities, have been published during the last decade. Hence, this fundamental support tool has been already adopted by every municipality that has a dense urban structure and a copious population or, for the cities where it is not yet, they are in the process of setting up 3D city models as part of the range of their planning tools. A further important pattern, as debated in the first chapter, concerns how 3D city models can be differently used in diverse purposes according to their features. Indeed, 3D city models change their characteristics in accordance with the purpose for which they are going to be used. In other words, every 3D city model can be created at five diverse LoDs and every level-of-detail is differently employed in every task since each of them, when is supported by a 3D city model representation, requires dataset of a certain minimum of LoD to be feasible.

Furthermore, through this dissertation it has been shown that 3D city models generation can occur as a time-consuming, expansive and complex process, which involves several phases to combine together these datasets. Therefore, to put things right throughout the whole procedure of 3D city modeling, it can be argued that some relevant considerations need to be taken into account before starting with the practical phase of the generation process. The first thing to do would be individuating those domains that are valuable and feasible for the context of interest. This would be an early stage that implies several preliminary studies such as, feasibility or environmental impact analyses as well as the engagement of different stakeholders through workshops or interviews, leading towards a user-oriented approach. Once do that, it would be necessary planning how to achieve the desired results and hence, individuating all the phases that have to be executed to accomplish the generation of a certain levels-of-detail 3D city model, which have to be suitable with the domains chosen. Therefore, the following phases of 3D city models generation have to take care of which data sources are needed to generate a certain LoD 3D city model, that will be a support tool for a specific purpose. After that, another consideration to take into account regards the choice of the adequate data acquisition methods to acquire those data formats. Once the data have been acquired, a suitable software to manage those file formats has to be chosen. Lastly, the most appropriate platform to display the LoD 3D city model generated has to be individuated, which has the important task to make the model appear attractive and useful for users.

In the light of that, it can be assumed that the demonstration developed in Vaxholm, on the one hand, has produced good results, providing an effective procedure, which could be taken as example for the 3D model generation of other cities that present similar characteristics. Additionally, even though the whole process developed turned out time-consuming, the 3D city model generated has brought valuable outcomes, given the complexity of the 3D building models and the combination of different workspaces together and considering that a large piece of territory as the whole island of Vaxön within more than two thousands buildings have been reconstructed. On the other hand, some limiting factors have emerged. Indeed, if the path followed to generate the models and the hypothetical optimal-effects procedure proposed above are compared, some gaps are visible throughout the approach conducted in Vaxholm. For instance, there is a lack of any kind of workshop or survey conducted with the engagement of stakeholders of different areas of expertise since the project developed has started as only an academic internship. Hence, the purposes identified in the beginning were only oriented towards providing a visual communication of planned developments in its environment through visualizations of and navigation in the 3D city model, where citizens could interact with the model. However, the citizens have been involved only once the model was already created using the former as basis for decision-making processes that involve the inhabitants of Vaxholm letting them express their opinion leaving feedbacks by e-mails. Nevertheless, even if after events, the result of the approach employed will most likely be improved over the coming years. Indeed, workshops conducted with the city departments of urban planning, facility management and citizens, can largely help with additional requirements and gathering fundamental information about hypothetical tasks to which extend the application of the 3D models, in order to define the intended support that a digital city can provide to them. Therefore, the resulting requirements using a user-oriented approach would aim to reflect the users needs and would take into consideration such purposes considered valuable for the environment.

Personally, I believe that this research might be helpful for all stakeholders involved in 3D city modeling community with different level of decision-making, in the way that they may use it to make improvements to their product or at least understand the range of applications that 3D geo-information can offer today. Also it might be beneficial as a reference that provides a detailed insight defining use case scenarios and then according to the purposes that have to be achieved, setting the suitable requirements when procuring the 3D datasets. Even though the large number of cases of study that have been mentioned, proves already the estimable role and the high demand of 3D city models, further technologies improvements, new scenarios and cases of application, are expected in the following years. One of the biggest task related to the field of 3D city models is to find cost-effective and avoid time-consuming approaches to create models rich of semantic information. For instance, improvements towards the integration of computer graphics, GIS and BIM, would allow on the one side, the realization of more detailed 3D city models within separable objects for larger geographic areas and on the other side, rich of information stored in the model would allow new types of applications to be planned and increasing the possibilities associated with 3D city models. Another example would be a shift of the main focus for the cases of application. Indeed, the majority of cases are focused on buildings, and not many require 3D models regarding other fundamental objects of the environment such as, vegetation, bridges and other kinds of infrastructures. Thus, it is expected that in the future, new cases will take advantage of these 3D elements other than the buildings. Another big issue emerged during this dissertation, is related to exchange formats, openness and interoperability in the field of geographic information. Unfortunately, due to the high costs of the majority of the software currently available in the market, as well as to the lack of guarantee that two files that have the same format will behave in the same way, it can be assumed that a lot of work is needed to achieve interoperability between diverse software and different environments and that the exchange of formats has to be specified in a completely clear manner eliminating possibilities of personal interpretation. Therefore, enhancement in this context would allow for more uniform workflows spending less time in finding errors.

In conclusion, in the light of the all above-mentioned considerations, it can be asserted that virtual city modeling for many municipalities is a new approach to manage cities development and to encourage participation of the public within the planning process. A 3D city model can help city, both similar and different from Vaxholm, to visualize, inspect, and communicate proposed developments and changes of their urban environment. The approach followed to generate the model, can be applicable in other context with similar characteristics, such as equal size, number of inhabitants, historical background and building structure, as a support tool for more transparent communication with the citizens that has the potentiality to improve the quality of the planning process. However, there is a lot more to investigate in this field that unluckily is outside the goal of this dissertation, but it clear that the more detailed is the model and rich of semantic information, the greater are the possibilities to include additional applications with the model as a basis

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