FEASIBILITY OF EXPLOITATION OF 3D CITY MODEL CREATED FROM LIDAR DATA AND AERIAL IMAGES IN APPLICATIONS FOCUSING ON CHAOPHRAYA RIVER BASIN AND THE AREA OF THE EASTERN ECONOMIC CORRIDOR (EEC) OF THAILAND

Nobphadon Suksangpanya (1), Chisaphat Supunyachotsakul (2)

[1] Department of Industrial Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Chalongkrung Rd., Ladkrabang, Bangkok, 10520, Thailand
[2] Department of Civil Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Chalongkrung Rd., Ladkrabang, Bangkok, 10520, Thailand

Email: nobphadon.su@kmitl.ac.th; chisaphat.su@kmitl.ac.th

KEY WORDS: Point Cloud, Features, Reconstruction

ABSTRACT: 3D city model and their variety applications has been of interests of many users especially the government entities. This is because the applications of 3D city model are tremendous. There are different approaches of creating 3D city model, generally, most of raw datasets used are the point cloud data obtained from the LIDAR (Light Detection and Ranging) technology and the aerial images. In Thailand, it has been of an interest if currently available LIDAR data and aerial images; which were collected over the area of Chaophraya river basin in Thailand, are able to be used for creating 3D city model. These collected datasets had not yet been proved their eligibility to do so. The goals/objectives of this study/project are (1) to study the feasibility of using the available LIDAR datasets and aerial images over the area of the Chaophraya river basin (data of MOST and JICA) to create 3D city model and to determine the possible applications that could make use of the to-be-created products, and (2) to suggest appropriate applications that make use of 3D city model data to be developed for the case of the Eastern Economic Corridor (EEC) of Thailand which covers the Chonburi, Rayong, and Chachoengsao. In this study, vigorous studying and testing were conducted to achieve the objectives of this project. Sets of 3D city model were created over different characteristics of area such as 3D city model in dense urban areas and 3D city model in low dense urban areas. These 3D city models were to be used as examples for estimating tasks in order to answer questions listed in the objectives of this study. Additionally, the aforementioned 3D city models were created by different approaches in order to investigate and study on the pros and cons of each approach considering on different quality of the datasets used. Furthermore, the recommendations are made on the aspects of expected properties and qualities of raw LIDAR data and aerial images to be used for creating 3D city model in the area of the EEC of Thailand as well as the potential usages/applications those 3D city model. Finally, this study also suggests the approach of exploiting a platform that can facilitate variety usages of 3D city model in many applications by developing a mock-up software to demonstrate such idea.

1. INTRODUCTION

The government of Thailand has driven the country into the digital era for years. The evolving technologies have forced the country to grow in all aspects, these include the economic aspect and the social aspect. The growing rate of the country is considered rapid and efficient ways of planning and management are necessary. The country needs appropriate data and tools to support related planning and management tasks such as the infrastructure network planning and management, the land usage planning, and the management of environmental impacts from urban growth and constructions. It is obvious that the fundamental data that is needed is the geospatial data of the country on which the analysis can be applied to extract required information in order to answer or solve specific problems. Beside 13 layers of the Fundamental Geographic Data Set (FGDS) of Thailand, 3-Dimensional city models are deemed to be a valuable dataset to be used in many applications.

Geo-Informatics and Space Technology Development Agency (Public Organization) or GISTDA which is a Thai government entity focusing on geoinformatics business and space activities has foreseen great benefits of having 3D city model for Thailand. GISTDA would like to know the feasibility of using the available LIDAR datasets which belong to the Ministry of Science and Technology (MOST) and Japan International Cooperation Agency (JICA) in any activities of 3D city model productions. The areas of focus are the area of the Chaophraya river basin where the LIDAR dataset covers. GISTDA would like to extend this feasibility study idea into the area of the so-called “Eastern Economic Corridor” or “EEC” of Thailand which covers Chachoengsao, Rayong, and Chonburi provinces. This became the objectives of this feasibility study project which are the followings:

Objective 1: To study the feasibility of using the available LIDAR datasets and aerial image over the area of the Chaophraya river basin (data of MOST and JICA) to create 3D city model and to determine the possible applications that could make use of the to-be-created products.

Objective 2: To suggest appropriate applications that make use of 3D city model data to be developed for the case of the EEC area.

2. RELATED THEORIES AND WORKS

Authors conducted the study and performed literature reviews on the previous researches and projects which related to this study. The related technologies will be covered in section 2.1 for giving readers basic understanding in LIDAR data which is considered as one of the main datasets of this study as well as the definition of the derived product “3D city model”. In section 2.2 covers the idea of the Level of Detail (LOD) for quantify the quality of created 3D city model in the sense of the resolution. Furthermore, in section 2.3 the researches and works related to this study which were conducted before will also be covered.

2.1 LIDAR Technology and 3D City Model

Light Detection and Ranging (LIDAR) is a technology that uses a laser scanner to obtain local information about the positions and reflectivities of the objects being surveyed. A basic LIDAR device combines a ranging instrument, a beam steering mechanism, and a sampling capability to produce discrete points in the surrounding 3D space. The fundamental result of this technique is known as the ‘‘point cloud.’’ This point cloud contains three-dimensional position and intensity data (X, Y, Z, I). The intensity data gives information about the reflectivity of the survey object surfaces under that scanning environment [Johnson, Bethel, Supunyachotsakul and Peterson, 2016]. The 3D point cloud data serves as a basic dataset that is used for creating other value-added products such as the digital terrain model (DTM), the digital surface model (DSM), the object models, and the 3D city model.

System that exploits LIDAR technology use laser scanner as its main mapping sensor in conjunction with other supporting devices. The main unit of the system will be mounted on a platform for operation and the platform can be either static or mobile one. The main components of the mobile LIDAR system include positioning unit (Global Navigation Satellite System (GNSS) receiver) for locating positions of vehicle (where system platform is mounted on) every instantaneous time and the Inertial Navigation System (INS) that consists of the Inertial Measurement Unit (IMU) for realizing the orientation of the platform.For this project the LIDAR datasets were collected with mobile airborne LIDAR system. Since airborne LIDAR system consists of many components, the quality of the obtained point cloud data does not depend only on any single element, however, it depends on the performance of all components altogether.

Point cloud data surveyed by the LIDAR system can be used for creating many derived products which can be used in many applications. Object models are one of the most popular products derived from LIDAR data. Stating of the objected models, this project does not focus on the models that do not consider the spatial accuracy into account (i.e. cartoon models), instead the models are to be used in spatially related analysis to answer variety location related problems. The 3D city model is a geometric representation of buildings and other city's features (Biljecki et al., 2015a). The example of 3D city model is shown in Figure 1

Figure 1 3D City Model of Berlin, Germany (from Virtualcitysystems [CC BY-SA 3.0 https://creativecommons.org/licenses/by-sa/3.0], via Wikimedia Commons)

The 3D city model can be created by different approaches/methods using different types of raw datasets. The examples are creating 3D city model with photogrammetry technique, creating 3D city model with point cloud data obtained from LIDAR system, and using combination of aerial images and LIDAR point cloud data together to create 3D city model.

2.2 The Idea of the Level of Detail (LOD)

The concept of the Level of Detail (LOD) is used when considering a set of 3D city model data in the sense of its resolution (how fine/how coarse). For a quality of a created 3D city model, there are two main aspects involved. First is about the spatial accuracy of the created 3D city model and second is about the completeness of the model. Quantifying degree of completeness of a 3D city model without mentioning which the LOD it refers to is not a valid approach.
Currently, there is no official international standard in defining the LOD of the 3D city model. The LOD standard defined by Open Geospatial Consortium (OGC) for 3D city model in the format of CityGML is popular and widely adopted, however, the LOD standard defined by the OGC is not set or officially declared as the international standard in this case. Consequently, when stating about the LOD of the 3D city model data, the speakers should always define the reference standard of LOD used. Different users may define their own LOD standard depending on their preferences and focuses. Many researchers have interest and performed studies in this issue with the goal to come up with effective standard to classify the LOD or to define the LOD standard of the 3D city model, therefore there are many LOD classification/standard proposed by different researchers. The examples are the studies of Biljecki et al. (2014) and Boeters et al. (2015)

In this project, the adopted LOD standard of 3D city model is the one adjusted from the original OGC standard. The LOD of 3D city model data is classified into 4 level (LOD0-LOD3) as shown in Figure 2 with description of each LOD class as followings:

- LOD0 of the 3D city model is the coarsest level of all, the model in this level is still a 2.5D DTM which has aerial images draped on. The estimated shape of the buildings can only be realized by looking at the buildings' footprints shown in the images.

Figure 2 Illustration of LOD classes for 3D city model adopted for this study (source: IGG Uni Bonn, http://www.citygml.org)

- LOD1 of the 3D city model is typically known in term of "block model". The shape and the structure of the buildings are represented by using simple geometry. The model in this level has no geometric representation of the buildings' roofs shape, instead they are represented by using flat surfaces.
- LOD2 of the 3D city model has some improvement from the LOD1, the building models are not just simple block models with flat surface rooftops, instead, LOD2 models depicts the shapes and structural differences of the buildings' roofs and facades in more detail.
- LOD3 of the 3D city model is typically known in term of "architectural model". The model in this LOD3 level depicts more detail of the buildings compared to previous levels LODs. Not only illustrating the details of roofs and facades, it also covers the details about other buildings' main components such as windows and doors.

In this study, the texture (not geometric detail) of city's main features is considered as the add-on information which can be integrated into city model of any LODs depending on the usage purposes.

2.3 Literature Reviews

As previously mentioned, the 3D point cloud data obtained from LIDAR system serves as a basic dataset that is used for creating other value-added products such as DTM, DSM, object models, and 3D city models. The applications of those products are tremendous and cannot be exhaustive listed. The applications could lead to the answers of many specific problems. Previous researches and studies have shown the value 3D city model in many applications, it is not limited in the science and engineering application only, but it also expands the usage of 3D city model data into many other different fields (Biljecki et al., 2015b, Batty et al., 2000, Ross, 2010). The examples of the applications of the 3D city model data are the use of 3D city model in analysis process to find the optimum positions for the installation of the solar cell panels (Biljecki et al., 2015b, Liang et al., 2015, Eicker et al., 2014, Santos et al., 2014, Hofierka and Kanuk, 2009), the use of 3D city model for studying and analyzing of the energy demands of the buildings (Kaden and Kolbe, 2014, Krüger and Kolbe, 2012, Carrión et al., 2010), the use of 3D city model for analyzing the buildings damage scale caused by the urban flood (Amirebrahimi et al., 2015), the use of 3D city model to study the noise pollution dispersion in the high traffic volume areas (Ranjbar, Gharagozlou and Nejad, 2012, Law et al., 2011, Stoter, Kluijver, and Kurakula, 2008, Kurakula, 2007, Czerwinski et al., 2006, Law, Lee, and Tai, 2006).

3. METHODOLOGY

This section will cover the detail of datasets used and describes the study approach adopted in this project in section 3.1 and 3.2, respectively.

3.1 Data Used

As previously mentioned, this feasibility study focusing on the possibility of using currently available LIDAR datasets and aerial imagery which belong to the Ministry of Science and Technology (MOST) and the Japan International Cooperation Agency (JICA) in any activities of 3D city model productions. The LIDAR datasets of MOST and JICA cover the area of the Chaophraya river basin as shown in green and pink color in the Figure 3, respectively. Not only the area of the Chaophraya river basin, this study also focuses on the EEC area which includes 3 provinces (Chachoengsao, Rayong, and Chonburi provinces) in the east region of Thailand as shown in the Figure 3. Examples of LIDAR data (point cloud) and aerial images over the Chaophraya river basin are shown in Figure 4

3.2 Study Approach

Based on the objective of this study that involves the evaluation of the possibilities in using 3D city model (created from the available datasets) in many applications. Since 3D city model applications are variety and cannot be exhaustively listed, it is then impossible to evaluate the use of created 3D city model in each application one at a time. For facilitating the evaluation process, all 3D city model applications must be grouped first. There is no fix rule in grouping or categorizing 3D city model applications, it is one of the design parameters in an experiment. For this study, the 3D city model applications are categorized into 4 main groups (branches) mainly based on differences in the minimum 3D city model qualities requirements which are: visualization, management, planning, and design.

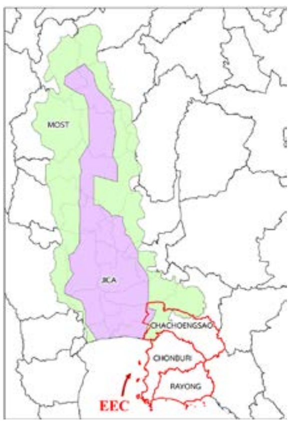

Figure 3 Extents of JICA, MOST, and EEC regions

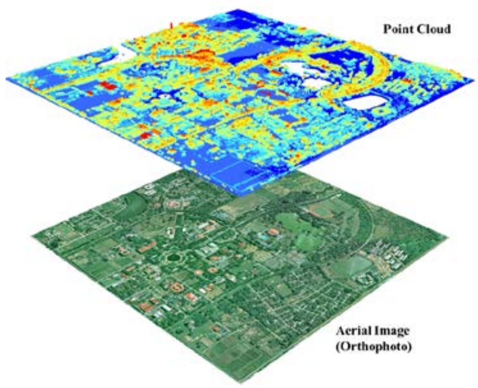

Figure 4 Example of point cloud dataset from LIDAR (top) and aerial image (bottom) in Nakhonprathom, Thailand

Once the groups of 3D city model applications have been set. The evaluation process can be performed by evaluating the possibility of using the created 3D city model in each application group one at a time. Based on the objective of this study, in order to achieve the objective 1) the approach as described below is adopted.

1. Selecting test datasets to be representative areas of the whole datasets. To do so, overall investigation on the LIDAR datasets and the aerial images covers the area of the Chaophraya river basin is performed. This is to see the variety of the datasets in order to appropriately select many smaller test datasets (LIDAR data and its corresponding aerial images) which could reflect all quality ranges of a whole datasets.
2. Using the selected test datasets to create 3D city models by using 3 different methods, those are creating 3D city model from LIDAR point cloud only, from aerial images only, and from both LIDAR point cloud and aerial images together.
3. Evaluating the possibilities of using those created 3D city models in each branch of applications.

Based on the objective of this study, in order to achieve the objective 2) studying economics of the EEC area is necessary, then the investigation of the topographic aspects of this area must be performed in order to point out any special applications of 3D city model (if necessary, beside the use of 3D city model in 4 main branches as adopted for the case of the Chaophraya river basin).

4. FINDINGS

The findings of this feasibility study are presented in this section, first the findings about the original datasets are described in section 4.1. The findings associated with the objective 1 and 2 will be shown in section 4.2 and 4.3, respectively.

4.1 Findings about the Original Datasets

From overall investigation on the LIDAR datasets and the aerial images covers the area of the Chaophraya river basin, the findings about these datasets are summarized as follows:

- LIDAR datasets qualities are similar in overall areas. There is no area that shown to have significant differences when compared to the others.
- The point cloud on the overlapped flight path area has point density of 0-4 point/m^2.
- The point cloud on the non-overlapped flight path area has point density of 0-1 point/m^2.
- The average positional accuracy of LIDAR datasets was reported as 1m in horizontal plane and 0.2m in vertical plane. The full accuracy assessment of the LIDAR point cloud is outside the scope of this feasibility study, therefore a rigorous approach for spatial accuracy evaluation of the point cloud was not conducted.
- The qualities of surveyed aerial images are similar in overall areas. There is no area that shown to have significant differences when compared to the others.
- The aerial images have the GSD of 20 cm.
- The average positional accuracy of aerial imagery was reported as 1m in horizontal plane. The full accuracy assessment of the aerial images is outside the scope of this study, hence a rigorous approach for spatial accuracy evaluation of aerial images was not conducted.

4.2 Findings of the Objective 1

The 3D city model datasets were created from the selected datasets (LIDAR data and aerial image) as mentioned above. The created 3D city models are shown in Figure 5 to Figure 7.

Figure 5 3D city model over rural (top) and urban (bottom) regions created by using point cloud and aerial image of MOST dataset

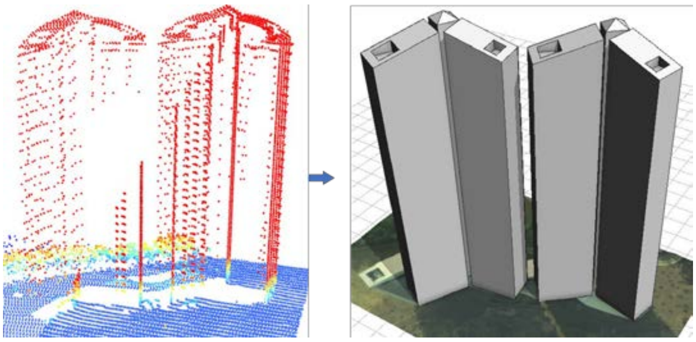

Figure 6 Point cloud of a condominium used for creating a detailed 3D city model

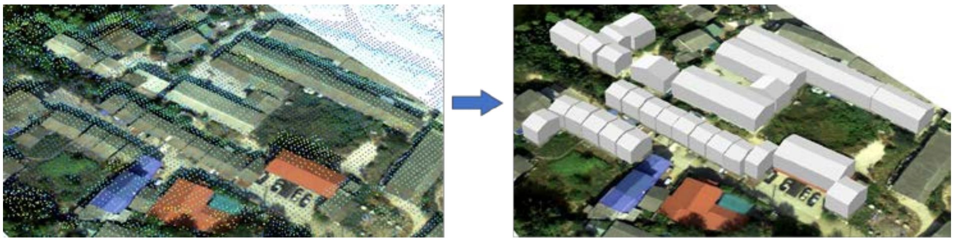

Figure 7 3D city model of building-dense area created from point cloud

The created 3D city model datasets were brought into the evaluation process. This is to check the possibilities of exploiting those 3D city model datasets in each of the 4 branches of applications, i.e. visualization, management, planning, and design. The evaluation results of the 3D city model datasets created from the original data over the Chaophraya river basin are captured in Table 1 to Table 4 to demonstrate the possibilities of exploiting those 3D city model datasets in each visualization branch, management branch, planning branch, and design branch of applications, respectively. Furthermore, there will be some examples of applications listed under each use cases in the tables.

In these table, the column "Requirements" in the tables displays the requirements of four aspects of the dataset which are positional accuracy (Ab Ac), relative positional accuracy (Re Ac), interior detail (Inte De), texture of surface (Tex). The requirement in these aspects is assessed and can be reported into 4 types which are:

- "Y" means Yes, i.e. this aspect is required for the dataset to be able to use in the application.
- "OP" means Optional, i.e. having this aspect is useful but is not required.
- "NN" means Not Necessary, i.e. having this aspect is not useful
- "-" mean Not Applicable, i.e. this aspect is irrelevant to the application.

In addition, the minimal LOD required for the dataset to be able to be used for the applications is suggested in the tables under the column "Required LOD". In the column "Required Semantic

Data”, some examples of semantic data required for the applications is stated. Finally, the last column of the tables shows the assessment of the available data from MOST over Chaophraya river basin which indicates whether the available LIDAR data or the available aerial images can be used to create the applications. Moreover, this study also assesses the case of using both LIDAR data and aerial images for creating the applications. The assessment results in various applications and use cases are shown in Table 1 to Table 4.

4.3 Findings of the Objective 2

Since many applications can be considered useful, this study suggests that the ECC region should have a multiple application module program. Concretely, such program is comprised of many different modules, each representing group of applications. The databases of this program are spatial data; such as point cloud, geo-referenced images, vector GIS, DTM, DSM, and 3D city models at various LOD. In addition, there should be various semantic data and its attribute available within the program. All data serves as database which facilitating the development of other applications by users and developers which encourages limitless possibility of usage.

Table 1 Requirements of data for creating visualization applications

	Visualization	Requirements				Required LOD	Required Semantic Data	Possibility of using available data		
		Ab Ac	Re Ac	Inte De	Tex			LIDAR	Aerial image	LIDAR + Aerial
	Walk through /Fly over									
1	Fly over (Outside)	NN	Y	-	OP	At least LOD1	-	Y	Y	Y
2	Tourism (Virtual tour - Outside)	NN	Y	-	Y	At least LOD2	-	N	N	Y
3	Tourism (Virtual tour - Inside)	NN	Y	Y	Y	At least LOD1	-	N	N	N
4	Flight simulation	OP	Y	-	OP	At least LOD1	-	Y	Y	Y
	Visibility Analysis (LOS)									
5	CCTV installation (outdoor)	OP	Y	-	OP	At least LOD2	-	N	N	Y
6	CCTV installation (indoor)	NN	Y	Y	OP	At least LOD1	-	N	N	N
7	Building construction analysis	OP	Y	-	NN	At least LOD2	-	N	N	Y
	Shadow Analysis									
8	Solar-cell installation analysis	Y	Y	-	OP	At least LOD2	Direction and position of the sun irradiation	N	N	Y
9	Shadow and shade casted by buildings	Y	Y	-	NN	At least LOD2	Sun angles based on time of the year	N	N	Y
10	Energy demand in building	Y	Y	OP	OP	At least LOD2	Earth surface temperature, etc	N	N	Y

Table 2 Requirements of data for creating management applications

	Management	Requirements				Required LOD	Required Semantic Data	Possibility of using available data		
		Ab Ac	Re Ac	Inte De	Tex			LIDAR	Aerial image	LIDAR + Aerial
	Asset Inventory									
11	Traffic signs	NN	NN	-	Y	At least LOD3	-	N	N	N
12	Electric poles	NN	NN	-	NN	At least LOD3	-	N	N	N
13	Manholes	NN	NN	-	Y	At least LOD3	-	N	N	N
	Pollution Monitoring									
14	Noise pollution analysis	Y	Y	OP	OP	At least LOD2	Construction materials, source of noise, level of noise, etc	N	N	Y
15	Wind analysis (e.g. wind turbine installation sites)	Y	Y	NN	NN	At least LOD1	Wind direction based on time of the year, temperature, etc	Y	Y	Y
16	Building Information Model (BIM)	NN	Y	Y	Y	At least LOD3	Construction materials, etc	N	N	N
	Disaster Management									
17	Flood	Y	Y	OP	OP	At least LOD1	Precipitation, water run-off, etc	Y	Y	Y
18	Windstorm	Y	Y	NN	NN	At least LOD2	Characteristics of the windstorm, etc	N	N	Y
19	Fire	Y	Y	OP	NN	At least LOD2	Fire origin and source, wind direction and velocity, etc	N	N	Y

Table 3 Requirements of data for creating planning applications

	Planning	Requirements				Required LOD	Required Semantic Data	Possibility of using available data		
		Ab Ac	Re Ac	Inte De	Tex			LIDAR	Aerial image	LIDAR + Aerial
	Preliminary Planning									
20	Building Construction Planning	Y	Y	NN	NN	At least LOD1	-	Y	Y	Y
21	Urban planning, land use zoning	Y	Y	NN	NN	At least LOD1	-	Y	Y	Y
22	Road network planning	Y	Y	-	NN	At least LOD1	-	Y	Y	Y
23	Railroad, subway, sky-train network planning	Y	Y	-	NN	At least LOD2	-	N	N	Y
24	Emergency response and evacuation planning	Y	Y	OP	OP	At least LOD3	-	N	N	N

Table 4 Requirements of data for creating design applications

	Design	Requirements				Required LOD	Required Semantic Data	Possibility of using available data		
		Ab Ac	Re Ac	Inte De	Tex			LIDAR	Aerial image	LIDAR + Aerial
25	Building maintenance	Y	Y	OP	NN	At least LOD3	-	N	N	N
26	As-build construction design	Y	Y	OP	NN	At least LOD3	-	N	N	N
27	Indoor renovation (ภายใน)	Y	Y	OP	NN	At least LOD3	-	N	N	N
28	Post construction QA/QC	Y	Y	OP	OP	At least LOD3	-	N	N	N
29	Earthwork quantities	NN	Y	-	NN	At least LOD1	-	Y	Y	Y
30	Bridge clearance monitoring and analysis	NN	Y	-	OP	At least LOD3	-	N	N	N
31	Powerline clearance monitoring and analysis	NN	Y	-	-	At least LOD3	-	N	N	N
32	Structure (building, bridge, pavement) surface health monitoring	NN	Y	-	Y	At least LOD3	-	N	N	N

5. CONCLUSIONS

The results obtained from this feasibility study help us see the fact about the quality of the current LIDAR data and aerial images. It is important to know whether current datasets can be used for 3D city model applications which is being of interest of many government entities in Thailand. The study results can be concluded as followings:

- There exist applications that make use of 3D city model in many countries but Thailand.
- The 3D city model applications were grouped into 4 main branches; those are visualization, management, planning, and design.
- The current LIDAR data and aerial images over the Chaophraya river basin can be used together for 3D city model creation at LOD2 with 95% manual works.

Furthermore, the study results suggest that regardless of the area of focus, for facilitating the development and the growing of the 3D city model applications in many aspects, the development of multiple application module program should be implemented.

6. REFERENCES

Amirebrahimi, S., Rajabifard, A., Mendis, P. and Ngo, T., 2016. A framework for a microscale flood damage assessment and visualization for a building using BIM–GIS integration. International Journal of Digital Earth, 9(4), pp.363-386.

Batty, M., Chapman, D., Evans, S., Haklay, M., Kueppers, S., Shiode, N., Smith, A. and Torrens,

P.M., 2000. Visualizing the city: communicating urban design to planners and decision-makers.
Biljecki, F., Ledoux, H., Stoter, J. and Zhao, J., 2014. Formalisation of the level of detail in 3D city modelling. Computers, Environment and Urban Systems, 48, pp.1-15.
Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S. and Çöltekin, A., 2015a. Applications of 3D city models: State of the art review. ISPRS International Journal of Geo-Information, 4(4), pp.2842-2889.
Biljecki, F., Heuvelink, G.B., Ledoux, H. and Stoter, J., 2015b. Propagation of positional error in 3D GIS: estimation of the solar irradiation of building roofs. International Journal of Geographical Information Science, 29(12), pp.2269-2294.
Boeters, R., Arroyo Ohori, K., Biljecki, F. and Zlatanova, S., 2015. Automatically enhancing CityGML LOD2 models with a corresponding indoor geometry. International Journal of Geographical Information Science, 29(12), pp.2248-2268.
Carrión, D., Lorenz, A. and Kolbe, T.H., 2010. Estimation of the energetic rehabilitation state of buildings for the city of Berlin using a 3D city model represented in CityGML. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci, 38(4), p.W15, pp.31–35.
Czerwinski, A., Kolbe, T.H., Plümer, L. and Stöcker-Meier, E., 2006, September. Spatial data infrastructure techniques for flexible noise mapping strategies. In Proc. of the 20th International Conference on Environmental Informatics-Managing Environmental Knowledge. Graz., pp.99-106
Eicker, U., Nouvel, R., Duminil, E. and Coors, V., 2014. Assessing passive and active solar energy resources in cities using 3D city models. Energy Procedia, 57, pp.896-905.
Hofierka, J. and Kanuk, J., 2009. Assessment of photovoltaic potential in urban areas using open-source solar radiation tools. Renewable Energy, 34(10), pp.2206-2214.
Johnson, S.D., Bethel, J.S., Supunyachotsakul, C. and Peterson, S., 2016. Laser Mobile Mapping Standards and Applications in Transportation.
Kaden, R. and Kolbe, T.H., 2014. Simulation-based total energy demand estimation of buildings using semantic 3D city models. International Journal of 3-D Information Modeling (IJ3DIM), 3(2), pp.35-53.
Krüger, A. and Kolbe, T.H., 2012. Building analysis for urban energy planning using key indicators on virtual 3D city models—the energy atlas of Berlin. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 39(B2), pp.145-150.
Kurakula, V., Skidmore, A.K., Kluijver, H., Stoter, J., Dabrowska-Zielinska, K. and Kuffer, M., 2007, March. A GIS based approach for 3D noise modelling using 3D city models. Enschede, The Netherlands: ITC.
Law, C.W., Lee, C.K. and Tai, M.K., 2006. Visualization of complex noise environment by virtual reality technologies. Environment Protection Department (EPD): Hong Kong, China.
Law, C.W., Lee, C.K., Lui, A.S.W., Yeung, M.K.L. and Lam, K.C., 2011. Advancement of three-dimensional noise mapping in Hong Kong. Applied Acoustics, 72(8), pp.534-543.
Liang, J., Gong, J., Zhou, J., Ibrahim, A.N. and Li, M., 2015. An open-source 3D solar radiation model integrated with a 3D Geographic Information System. Environmental Modelling & Software, 64, pp.94-101.
Ranjbar, H.R., Gharagozlou, A.R. and Nejad, A.R.V., 2012. 3D analysis and investigation of traffic noise impact from Hemmat highway located in Tehran on buildings and surrounding areas. Journal of Geographic Information System, 4(04), p.322.
Ross, D.I.L., 2010. Virtual 3d city models in urban land management. Technischen Universitat, Berlin.
Santos, T., Gomes, N., Freire, S., Brito, M.C., Santos, L. and Tenedório, J.A., 2014. Applications of solar mapping in the urban environment. Applied Geography, 51, pp.48-57.
Stoter, J., De Kluijver, H. and Kurakula, V., 2008. 3D noise mapping in urban areas. International Journal of Geographical Information Science, 22(8), pp.907-924.