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MODEL-DRIVEN AND DATA-DRIVEN APPROACHES USING LIDAR DATA: ANALYSIS AND COMPARISON

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ABSTRACT:

Following the development of 3D data acquisition techniques like digital photogrammetry, remote sensing and airborne laser scanning, the automatic building modelling is still a challenging task. Indeed, it takes a growing place in many research fields like 3D city modelling, cartographic analysis, urban planning, visualization and Geographic Information Systems (GIS) database construction. Generally, two types of approaches characterize the automatic building reconstruction. The first one is a model-driven approach. This parametric modelling approach consists of searching the most appropriate model among basic building models contained in a models library. The second one is a data-driven approach, also called non-parametric modelling approach. This technique attempts to model a primitive or a complex building by using series of more or less complex operations. It allows the generation of a model without belonging to a specific library. After an extensive state of the art, this paper confronts methods belonging to each type of automatic building construction approach. Based on a concrete experiment, the essential points characterizing each approach, including their concept and the obtained model characteristics are analysed. It is of great interest to study these issues, since not many of such investigations have been made before and have delivered the useful formulas. Consequently, improvements are introduced and have led to develop a new method for each approach. After comparison of the accuracy of these two methods and the characteristics of the resulting models, some solutions and recommendations are proposed.

1. INTRODUCTION

Generally, in different surveying domains like city modelling, database construction of GIS, cartographic analysis or urban planning, 3D building modelling becomes an important common technique. The majority of available building modelling methods requires manual intervention. In the last ten years the research of automatic methods has grown by reason of the informatics progress. Currently, many automatic building modelling approaches have been carried out, but some limitations are inherent to each one of them. So the automation of a building modelling process still remains a challenging task.

The presented study focuses on automatic building modelling using airborne laser scanner data. After the acquisition of 3D city laser data, the 3D point cloud has to be segmented into three main classes: terrain, vegetation and buildings. Several approaches have been developed to carry out the Lidar data segmentation automatically like the approaches suggested by (Tarsha-kurdi *et al*., 2007a; Tóvári and Vögtle, 2004). Once the building point clouds are extracted, the automatic building modelling procedures can begin.

The definition of building modelling in the laser scanning domain is the construction of a 3D model of buildings composed of planes and edges extracted from the building point cloud. According to the literature (Maas and Vosselman, 1999), there are two principal approaches of building modelling starting from airborne laser scanner data: the model-driven or parametric approach and the data-driven or non-parametric approach. This study aims to compare both techniques in order to be able to conceive an optimized technique.

2. RELATED WORK

As mentioned above, two kinds of approaches characterize automatic building reconstruction: the model-driven approach and the data-driven modelling approach.

The model-driven approach makes beforehand a selection between the primitive and the complex buildings. So for a point cloud acquired on a primitive building the approach consists of searching the most appropriate model among basic building shapes contained in a models library. Then the most probable parameter values are calculated and assigned to the parameters of the selected model. Several solutions based on this approach have been developed. For instance, (Maas and Vosselman, 1999; Maas, 1999) propose a method based on the analysis of invariant or static moments of building point clouds. Another method has been presented by (Weidner and Förstner, 1995; Weidner, 1996) and concerns the automatic extraction of model-driven and prismatic building models from dense digital elevation models generated by photogrammetric techniques or airborne laser scanning. In addition to the last two methods, (Schwalbe *et al*., 2005) developed a method based on the use of the building vertical profiles. At last, several authors, e.g. (Haala *et al*., 1998; Brenner and Haala, 1998) suggest the introduction of the DSM (Digital Surface Model) surface normals.

In the case of complex buildings, several authors suggest to segment the complex building point cloud into primitives using ground plans or another type of additional data (Brenner and Haala, 1998; Haala *et al*., 1998; Schwalbe *et al*., 2005; Park *et al*., 2006). Then, every building can be handled independently.

The data-driven approach models a building regardless of its form. So it attempts to model a primitive or a complex building by using the point cloud as initial data. Thus, after series of more or less complex operations, this technique allows generating models without belonging to a specific library. Many works can be cited and classified in four categories:

Methods using the 3D Hough-transform: (Vosselman and Dijkman, 2001; Oda *et al*., 2004) use it for detecting the roof planes; (Hofmann, 2004) introduces it for the analysis of tin-structure parameter spaces.

Methods using the RANdom SAmpling Consensus algorithm (RANSAC): For instance (Ameri and Fritsch, 2000; Brenner, 2000) use it for detecting the roof planes. So planes are accepted or rejected based on a list of rules which present the possible relationships between planes and ground plan edges.

Methods using a region growing algorithm: (Alharthy and Bethel, 2004; Elaksher and Bethel, 2002) developed an algorithm that gathers together all pixels fitting a plane in raster data; (Rottensteiner, 2003) extracts roof planes using seed regions and applies a region growing algorithm in a regularized DSM. Then, the homogeneity relationships between the neighbour points are evaluated by calculating the point normals.

Methods using Douglas-Peucker technique: (Wang *et al*., 2006; Tarsha-kurdi *et al*., 2007a) propose to construct the facade models before studying the roof construction; so the resulting 3D building model is firstly constructed with plane roofs. They use Douglas-Peucker technique to segment the building contour polygon according to its facades.

Complementary data like ground plans are sometimes used in addition to the building point cloud (Ruijin, 2004; Vosselman and Dijkman, 2001; Haala *et al*., 1998).

Before comparing concretely each approach, it is necessary to detail them in the next paragraph.

3. MODEL-DRIVEN APPROACH FOR BUILDING RECONSTRUCTION

Since the model-driven approach searches the most appropriate model among basic building models contained in a library, it requires the extraction of the primitive buildings composing the area under study. The primitive building is a simple building which can be described by a set of parameters. The values of the parameters are calculated before constructing the 3D model. In the next step, the building roof details can be determined and then constructed.

As already mentioned, in the case of a complex building, many authors suggest to segment it into primitive buildings using the building ground plan. This decomposition can also be done through the building roof breaklines derived from the DSM. Figure 1 shows a successful and a failed result of this decomposition when applied on two different point cloud densities. The reliability of this latter method depends not only on the point cloud density, but also on the roof plane surfaces, the quantity and the dimensions of details occurring on the building roof.

In general, the parameters describing a building in a model-driven approach are of two types: parameters defining the building ground polygon (footprint parameters) and parameters describing the building space (space parameters). The first set of parameters defines the building footprint position, orientation and dimensions in addition to the building facades equations. The second set of parameters defines the building roof plane equations.

Based on these two parameter sets, the 3D building model can be constructed.

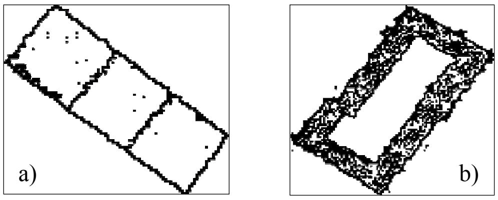

Figure 1. Test point cloud: a) Successful building breaklines extraction from a DSM (point cloud density: 7 points/m²); b) Failed building breaklines extraction from a DSM (point cloud density: 1.3 points/m²).

4. DATA-DRIVEN APPROACH FOR BUILDING RECONSTRUCTION

The data-driven approach usually assumes that a building is a polyhedral model. It attempts to model an unspecified building without segmenting it into primitives. It analyzes the building point cloud as a unity, without relating it to a set of parameters. This modelling category proposes series of operations allowing initially to generate an unspecified 3D building model starting mainly from the laser data. In spite of the probable risks of obtaining deformed models, it remains the only approach which treats the general case of unspecified building, i.e. as well the case of a complex building as the case of buildings blocks. Regardless of the used methods, the modelling is composed of two stages: building roofs modelling and facades modelling.

Concerning the building roof modelling, different methods have been evoked previously to detect the roof planes, like the RANSAC technique, the 3D Hough-transform and the region growing algorithms. These methods use sometimes complementary data in addition to the building point cloud, either to improve the plane roof detection or segmentation, or to improve the 3D building model quality. The next step is the determination of the neighbourhood relationship between the building roof planes. That is why (Ameri and Fritsch, 2000) propose to use the Voronoi diagram. Then, according to (Rottensteiner and Briese, 2003), the mutual relations between every two neighbour roof planes have to be determined (intersection, step edge or intersection and step edge together).

For the purpose of building facades modelling, two possibilities exist. The building contour polygon has to be detected either before segmenting the roof in planes, or after the building roof segmentation. In the first case, it is necessary to use line generalization algorithms which allow simplifying or segmenting the building contour polygon according to its facades like for instance the Douglas-Peucker technique. In the second case, the building contour polygon is segmented automatically following to the roof segmentation. The difference between these two cases is that in the first one, one facade is presented by several vertical planes according to the number of their adjacent roof planes. Whereas in the second case, one facade is presented by only one plane, under the assumption that the facade was previously well filtered (noise attenuation).

5. MODEL-DRIVEN AGAINST DATA-DRIVEN APPROACH: EXAMPLE OF BUILDINGS IN STRASBOURG CITY

The aim of the following example is to compare the accuracy and the quality of the 3D building models generated by the two approaches. For testing a model-driven approach, the method based on the analysis of invariant or static moments as initiated by (Maas and Vosselman, 1999; Maas, 1999) has been adapted and applied. For applying a data-driven approach, a method based on the Douglas-Peucker algorithm and the RANSAC technique has been extended and developed as initiated by (Ameri and Fritsch, 2000; Tarsha-kurdi *et al*., 2007a).

The data used is a point cloud located along the Rhine river, in the "Bord de Rhin" quarter of Strasbourg city (Fig.2). As it will be seen later, the data-driven approach is only applicable in the case of primitive buildings. That is why, the test area has been chosen in order to contain primitive buildings with gable roofs and some trees. The point cloud density is 1.3 point/m². Only the first pulse is available.

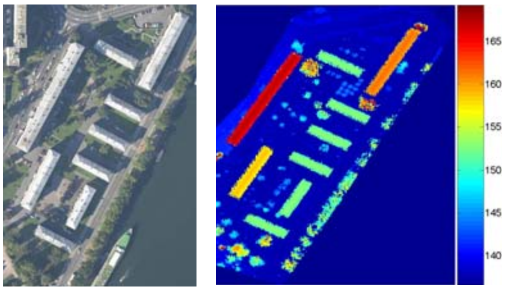

Figure 2. Aerial image and DSM of the sample used

5.1 Model-driven approach

The use of the analysis of static moments of a building point cloud implies two main processing steps. Firstly, the building point cloud has to be projected onto a horizontal plane in order to calculate the building orientation and the footprint parameters in 2D (Fig.3). Then, the process is continued in order to provide the 3D parameters of the building. After projection, the whole set of "new" points presents almost the building footprint form. The new points can be considered as infinitely small elements. Therefore, the application of the static moment equations on the new point cloud allows calculating the geometric elements of the building footprint, like the gravity centre of the building footprint (Equation 1) and the principal axes orientation (Equation 2). Figure 3b shows the coordinates system occurring in the calculation. Equation (3) presents the transformation from the original coordinates system OXY to the building footprint principal axes system O' X'Y'.

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \qquad \overline{Y} = \frac{\sum_{i=1}^{n} Y_i}{n} \tag{1}$$

Where n: point number; Xi and Yi: point cloud abscissas and ordinates in OXY.

$$\theta = \frac{1}{2}\arctan\frac{2\sum_{i=1}^{n}(X_i-\overline{X})(Y_i-\overline{Y})}{\sum_{i=1}^{n}(X_i-\overline{X})^2-\sum_{i=1}^{n}(Y_i-\overline{Y})^2} \tag{2}$$

Where θ: rotation angle between original coordinates system OXY and building footprint principal axes O'X'Y'.

$$\begin{aligned} X_i^{'} &= (X_i-\overline{X})\cos(\frac{\pi}{2}-\theta)-(Y_i-\overline{Y})\sin(\frac{\pi}{2}-\theta) \\ Y_i^{'} &= (X_i-\overline{X})\sin(\frac{\pi}{2}-\theta)+(Y_i-\overline{Y})\cos(\frac{\pi}{2}-\theta) \end{aligned} \tag{3}$$

If the building footprint form is known, its dimensions can also be calculated. Hence when the building footprint is rectangular, the equations (4) are used to calculate the length L_X and width L_Y of the building footprint.

$$L_x = \sqrt{\frac{12\sum_{i=1}^{n} X_i'^2}{n}} \qquad L_y = \sqrt{\frac{12\sum_{i=1}^{n} Y_i'^2}{n}} \tag{4}$$

The whole parameters can be calculated under the condition that the building point cloud has a homogeneous density.

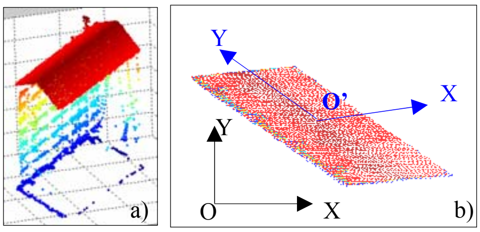

Figure 3. a) Visualization of the 3D building point cloud; b) Projection of the building point cloud on the horizontal plane of the original coordinates system OXY (O'X'Y': Principal axes of the coordinates system related to the building footprint; O': Building footprint gravity centre)

In this context, this method has been improved in order to be appropriate for irregular point distributions and for different densities of point clouds. Indeed, by creating a new point cloud generated from the building DSM, a homogeneous point density can be reached even if the data are slightly smoothed by the interpolation. So, this procedure is used to decrease the errors made in the calculation of the coordinates of the building gravity centre and of the building footprint dimensions. Moreover, the second new idea is to use the histogram of the original point cloud to extract especially the roof points and to continue the parameter calculation.

These additional operations improve on the one hand the building type determination, because it allows eliminating the "noisy" points (roof details, ground points). On the other hand, it enables to increase the precision of the determination of the building parameter values. Indeed, as illustrated in Fig.4a, the histogram analysis of the Z values occurring in a primitive building point cloud shows the possibility to divide the building point cloud into four parts: surrounding building points (I), facade points (II), roof points (III) and roof detail points (IV).

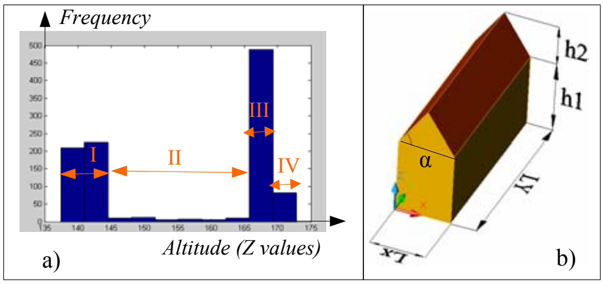

Figure 4. a) Histogram of the Z values of a building point cloud b) Primitive building parameters (where I: Surrounding building points; II: Building facade points; III: Building roof points; IV: Building roof detail points)

Once the building footprint principal axes are calculated and the building roof points are detected, the roof type can be determined and the building space parameters can also be calculated (h1, h2 and α). Fig.4b shows those parameters referred to a primitive building.
At this stage, the total 3D building model (Fig.5) can be constructed.

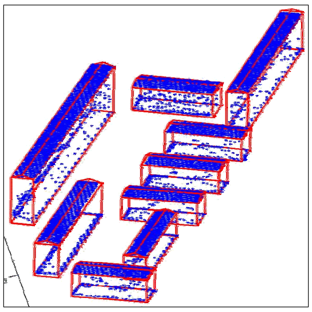

Figure 5. Superimposition of the building point clouds over the 3D parametric obtained models

Regarding the computing time, it can be noted that the model-driven approach is very fast, because it calculates only the values needed for defining the building parameters. On the other hand, it is limited by the fact that it is only reliable for primitive buildings having known footprints.

5.2 Data-driven approach

The data-driven method applied to the sample consists of two steps: building facades modelling and building roof modelling. After detection of the building contour polygon, this polygon is segmented according the building facades using the Douglas-Peucker algorithm (Douglas and Peucker, 1973). Then the equations of the facade planes are fitted based on the least square principle and the intersection between every two adjacent planes is calculated. These processing steps lead to the construction of 3D building models with plane roofs (Tarsha-kurdi *et al*., 2007a) as shown in Fig.6a.

The second step focuses on the modelling of the roofs. So, an extended RANSAC technique is applied to detect the roof planes (Tarsha-kurdi *et al*., 2007b). Then, the neighbourhood relationship between roof planes is formalized using the neighbourhood matrix which represents the Voronoi diagram of the label image. Finally, the mutual relations between every two adjacent roof planes have to be determined. At the same time, the intersections between the roof planes (adjacent to building contour) and the building facades are calculated. The two last steps allow constructing the total 3D building models (Fig. 6b).

The new idea introduced in this data-driven method consists in combining the Douglas-Peucker and the RANSAC algorithms. Indeed, it allows modelling the facades and the roof separately and helps to decrease the deformations quantity of the final building model. Moreover, the extended RANSAC technique allows harmonizing the mathematical aspect of the classical RANSAC algorithm with the geometry of a roof (Tarsha-kurdi *et al*., 2007b).

In the last paragraphs, one method of each approach types of automatic building modelling have been presented and applied concretely on a data set. In order to compare them, several items will be analysed like the 3D accuracy, the characteristics of obtained models, the advantages and disadvantages of each one.

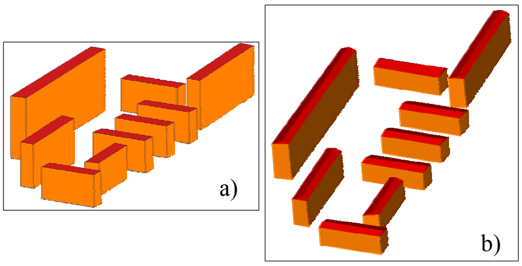

Figure 6. Application result of data-driven approach.
a) 3D building models with plane roofs
b) total 3D building models

5.3 Comparison of the accuracy of both approaches

In order to compare the two approaches regarding the accuracy of their resulting models, a 3D reference model of a set of nine building is created by semi-automatic photogrammetric digitizing. Its accuracy is about ±20 cm in X, Y, Z. All the buildings used in the sample present gabled roofs (Fig.2). The parameters extracted from these reference buildings are the footprint parameters (Lx and Ly) and the space parameters (h1, h2 and α).

Thus, three sets of parameters are calculated for each building: one set for the reference model, one set for the model-driven approach and at last one set for the data-driven approach. Then, the differences observed in the building parameters are compared with the reference building parameters. Also the mean of the parameter differences are calculated in addition to their standard deviations (Table 1).

Parameters		Footprint parameters		Space parameters		
Approach		ΔLx (m)	ΔLy (m)	Δh1 (m)	Δh2 (m)	$\Delta\alpha$°
data-driven	Mean	0,12	0,04	0,42	-0,29	-2,75
	σ	0,38	0,97	0,97	0,37	3,42
model-driven	Mean	1,24	1,47	0,23	-0,06	-2,6
	σ	0,65	0,52	0,97	0,34	3,08

Table 1. Mean parameter differences and standard deviation values obtained with each approach.

Table 1 shows that the footprints parameters in the data-driven approach are more reliable than those in the model-driven approach. Indeed the mean values confirm this tendency since the footprint parameters are closer to the real values (0.12< 1.24 and 0.04 < 1.47). The slight difference observed between the total standard deviations (1.04 > 0.83) is not significant enough to contradict previous remark. Moreover, it can be observed that the space parameters in the model-driven approach are slightly more accurate than those in the data-driven approach. The mean values are systematically lower. Also, the standard deviations confirm this conclusion.

Another interesting way to compare both approaches consists in listing the techniques used in 3D building models calculation. Table 2 classifies the techniques used in 3D building models calculation into two families. The first family contains techniques based on a pure mathematical principle (PMP), e.g. calculation and intersection of plane equations. The second family is based on image processing principles (IPP), e.g. histogram analysis. Additionally, Table 2 contains signs (+,–)

for summarizing the accuracy results of Table 1. For example, the footprint parameters are more accurate (sign +) in the data-driven approach than in the model-driven approach (sign –).

	Footprint parameters	Space parameters
data-driven	(+) Douglas-Peucker (**IPP**)	(–) Calculation and intersection of plane equations (**PMP**)
model-driven	(–) Analysis of invariant moments (**PMP**)	(+) Histogram analysis (**IPP**)

Table 2. Techniques used in 3D building models calculation (**PMP:** Pure Mathematical Principle; **IPP**: Image Processing Principle)

It can be observed that the accuracy of the final calculated model is less related with the type of the modelling approach (model-driven or data-driven) than with the nature of the operations composing each approach. So, regardless of the modelling approach type, when pure mathematical principles are used on the whole cloud (such as the analysis of static moments, or calculation and intersection of plane equations) results will be less accurate than when image processing principles are used (like for example Douglas-Peucker technique and histograms analysis).

5.4 Comparison of the characteristics of the resulting models

The advantages of a model-driven approach are that it provides geometrical models without visual (geometric) deformations, because it is based on the calculation of values of parameters. Thus, it is important to underline the high computing speed gained by these approaches in comparison with data-driven ones. The only errors in this type of model can come from the calculation of the building parameters values. Moreover, the failure probability in choosing a building type among the model library is limited, because the number of thresholds needed for calculation is very small.

The major disadvantage of a model-driven approach is to be dependent on the buildings types which are available in the building library.

The essential advantage of data-driven approach is that the case of an unspecified building is studied, i.e. as well the case of a complex building as the case of building blocks. On the other hand, among several disadvantages, the considerable visual deformations produced by the data-driven approach of a complex building can be cited. Indeed, during the calculation of the building roof edges, the use of plane intersections presents real risks of misconstruction. The causes of possible misconstructions are listed below:

- In the general case, building modelling is based on the assumption that a building is composed of planes and lines (edges of the building). It is well known that building surfaces do not present planes in a mathematical sense. Thus, an equation of plane deduced from the points distributed on roof planes does not perfectly characterize a roof, but only approximates it.
- The point coordinates can contain errors (position inaccuracy, artefacts, and multi ways).
- The irregularity of the point distribution on the building roof can increase the errors. Indeed, inside the same surface of a building roof, it is possible to find variable points distributions.
- The point cloud density influences drastically the level of deformations. If the density increases, the quantity of deformations decreases and vice versa.
- The point cloud interpolation can generate a positive effect and a negative one simultaneously. On the one hand, it allows to eliminate the building facade points, to obtain a regular point grid and to smooth a large quantity of errors (bilinear or bicubic interpolation). In addition, it generates undesirable effects if the sampling interval chosen for the grid cells does not correspond to the density of points or if some parts of the point cloud are empty.
- The noise and the building roof details can be considered as obstacles because of the intolerable deformations which they could generate in the final model.

Several solutions were proposed in the literature in order to try solving this problem of deformations occurring in the data-driven approach:

- Application of geometrical constraints in the parallelism and the orthogonal level for calculating the roof plane edges (Haala and Brenner, 1997).
- Determination of the principal axis of each roof plane to observe the symmetry conditions (Elaksher and Bethel, 2002).
- Reiteration of calculation to eliminate the points having large residues (Rottensteiner and Briese, 2003).
- Preprocessing of the point cloud or of the DSM in order to eliminate the noise and to obtain homogeneous data (Alharthy and Bethel, 2004).
- Application of mathematical morphology operations which allow improving the forms of the obtained plan segments (Rottensteiner, 2003).
- Application of filters to eliminate the undesirable points before beginning the calculation (Haala and Brenner, 1997).

In some cases, each one of the propositions listed above improves the obtained models. But at the same time, in other cases, it can produce errors in the form obtained for the reconstructed building. In the algorithm we developed for the experiment, no specific improvement operations of the last list are applied. Two reasons explain this decision: The first one is the wish to avoid the negative consequences of some proposed improvements; the second one is that the buildings used in this experiment are relatively simple, so the foreseeable deformations are negligible. Additional tests need to be carried out in order to generalise our remarks to a greater set of building types.

6. CONCLUSION

This paper achieves a comparison between the data-driven and the model-driven approaches. Several 3D buildings resulting from the application of each approach are compared and confronted with a reference 3D model. Thus, the accuracy and the reliability of each modelling approach have been evaluated. Furthermore, one new method based on improved modelling principles has been proposed for each approach. These improvements increase the potential of the modelling method and the final model accuracy.

In summary, the model-driven approach considers the entire building point cloud. Its main advantages are that it provides in a very fast way geometrical models without visual deformations. On the other hand, the data-driven approach tends to simulate each part of the building point cloud for obtaining the nearest or the more reliable polyhedral model. Its main disadvantages are that it provides models with visual deformations and it needs more processing time. Nevertheless, if the point cloud is characterized by a homogenous distribution and if its density is in relation to the elements dimension which are relevant to be extracted (building roof, roof details), then the obtained data-driven model will be very faithful to the original building.

Concerning the model precision, it can not be said in the general case that the data-driven or the model-driven approach is more accurate than the other. Indeed, the model accuracy is more related to the techniques used in building modelling approaches than to the approach type. Nevertheless, in spite of the probable risks of obtaining deformed models, the data-driven approach remains the only approach which treats the general case of building of an unspecified form. Finally, further experiments should confirm these conclusions and improve the data-driven approach for generating a realistic and accurate 3D model.

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