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# A graph edit dictionary for correcting errors in roof topology graphs reconstructed from point clouds

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ABSTRACT

In the task of 3D building model reconstruction from point clouds we face the problem of recovering a roof topology graph in the presence of noise, small roof faces and low point densities. Errors in roof topology graphs will seriously affect the final modelling results. The aim of this research is to automatically correct these errors. We define the graph correction as a graph-to-graph problem, similar to the spelling correction problem (also called the string-to-string problem). The graph correction is more complex than string correction, as the graphs are 2D while strings are only 1D. We design a strategy based on a dictionary of graph edit operations to automatically identify and correct the errors in the input graph. For each type of error the graph edit dictionary stores a representative erroneous subgraph as well as the corrected version. As an erroneous roof topology graph may contain several errors, a heuristic search is applied to find the optimum sequence of graph edits to correct the errors one by one. The graph edit dictionary can be expanded to include entries needed to cope with errors that were previously not encountered. Experiments show that the dictionary with only fifteen entries already properly corrects one quarter of erroneous graphs in about 4500 buildings, and even half of the erroneous graphs in one test area, achieving as high as a 95% acceptance rate of the reconstructed models.


## 1. Introduction

Buildings are the dominant type of manmade objects in urban scenes. In the past decades methodologies have been developed to automatically reconstruct building models from digital surface models or airborne laser scanning data at the CityGML level of detail 2 (LoD2) (Kolbe et al., 2009). Although research has progressed significantly, the reconstruction problem is still challenging. Building reconstruction from point clouds has two major problems: data insufficiency and building type complexity. Lack of data representing the roof surfaces may be caused by a low point density of the laser scanning survey, reflectance properties of the roof material, and the presence of structures on top of the roof (chimneys, antennas). The detection of planes or shape primitives in the point cloud is obviously much affected by the amount of available data. Building type complexity is a problem as a modelling strategy needs to be able to deal with a very large diversity of building structures. Even when only considering planar roof surfaces, the number of possible building types is huge. The building complexity brings challenges to the construction of a library of building model primitives.

Roof topology graphs are widely used to reconstruct building models. Many researchers use model driven methods to search building primitives (Haala et al., 1998; Lafarge et al., 2010). Model driven methods are robust to reconstruct buildings, because they can easily combine building knowledge with data. As the search directly compares models with raw data (i.e. the point cloud), the procedure is time consuming. In order to speed up the search Verma et al. (2006) utilize roof topology graphs and search the primitives in the topology space. The raw data is transformed into higher-level information. Therefore, the search effort is much lower. However, the building primitives are limited to a few simple ones. Oude Elberink and Vosselman (2009) expand the primitive library and use graph matching to search primitives. The topology graphs are also used to interpret building structures in many other works (Sampath and Shan, 2010; Lafarge and Mallet, 2011; Zhou and Neumann, 2011; Perera et al., 2012). All methods assume the topology graphs are correct. The fact, however, is that the graphs are frequently incorrect because of lack of data and resulting errors in pre-processing steps, like classification and segmentation. For

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example, Sampath and Shan (2010) mentioned that small roof faces could not be detected. Therefore, their nodes are also missing in the roof topology graphs and the reconstructed models will be erroneous.

Our aim is to automatically correct the errors in roof topology graphs. In this paper we introduce a graph edit dictionary for this purpose and treat the graph correction problem similar to the spelling correction problem. Input data graphs are transformed to correct ones by several editing operations. The errors in the input graph usually occur as sub-graphs, which repeat in other buildings. The erroneous sub-graphs and their corrections are stored together as entries and explanations in a graph edit dictionary (GED). A graph matching algorithm searches the most likely error block in the input graph by comparing it to all entries in the dictionary. As the graph correction would need several transitions, a heuristic search is used to iteratively arrive at the optimal graph.

We developed a set of interactive editing tools to correct roof topology graphs. These tools are used to manually construct the correct graphs for the frequently occurring erroneous graphs, but are also useful to correct the remaining complex errors that cannot be dealt with by applying the graph edit dictionary. To terminate the automated graph correction procedure we need a criterion to decide whether a reconstruction is good enough. We introduce a simple criterion for accepting a reconstructed building model and enrich the roof topology graphs with local quality measures for individual nodes and edges to analyse which parts of the graphs need to be corrected.

The remainder of this paper is organised as follows: The related literature will be reviewed in Section 2. In Section 3 we will present an overview of the proposed method. The innovative components of this method will be presented in more detail in Section 4. In Section 5 we discuss the results of our method as applied to a dataset of Vaihingen, Germany, and Enschede, the Netherlands. The article ends in Section 6 with concluding remarks, a discussion of open questions and suggestions for further work.

## 2. Related work

In this section we first review literature on reconstructing building models. This is followed by a short discussion of literature on spelling correction and graph matching which will be used as reference for the graph correction method introduced in this article. We also explain how this relates to our work.

### *2.1. Building reconstruction*

Three types of approaches have been developed to reconstruct LoD2 building models from point clouds and DSM: mesh simplification, fitting of building shape primitives, and segment based methods. There are several review papers on the building reconstruction methods (Vosselman, 2002; Hu et al., 2003; Brenner and Von Goesseln, 2004; Haala and Kada, 2010). Mesh simplification is initially used to speed up visualization, delivery and storage (Garland and Heckbert, 1997). Wahl et al. (2008) use it to rapidly generate 3D city models. In order to keep sharp features (like plane intersections) and topological relationships, topology constraints are introduced (Wahl et al., 2008; Verdie et al., 2011; Zhou and Neumann, 2011). The mesh models are geometrically close to the raw data, and when textured, are close to the reality. Because no assumption about building shapes is needed, the mesh model is able to represent diverse building structures. This representation, however, does not contain semantic information as one roof face would be represented by several triangles. Besides, the models sometimes include artefacts caused by outliers that are included in the triangulation.

Fitting of building shape primitives, which have few parameters and predefined topologies, are used to model buildings in low resolution data in the early research. The point clouds from dense matching or lidar were noisy and sparse at that time. Therefore, the building roof structure could not be inferred from the original data by bottom-up methods. Additional data and building knowledge was necessary. Haala et al. (1998) use building primitives, like pent, flat, gable, and mansard roof, to represent building parts. Usually a 2D map with building footprints is used as extra information. However, these basic parametric shapes are not diverse enough to generate precise building models with arbitrarily shaped footprints. To overcome this limitation, Taillandier (2005) reconstructs buildings by extruding given footprints to a uniform building eave height. Building footprints are decomposed into cells. Each one is used as the footprint of a building primitive (Haala et al., 2006; Kada and McKinley, 2009). After the 3D primitives have been constructed for all cells, they are combined in a CSG-like manner to form a complex building model. Lafarge et al. (2010) use a Markov Chain Monte Carlo sampler (MCMC) and simulated annealing to find the optimal configuration of building primitives. Huang et al. (2011) narrow down the possible moves in the jump routine by only allowing change of a limited number of parameters in each step under some rules. This strategy could speed up the search but as it is a kind of blind search in which the convergence is rather slow. Suveg and Vosselman (2004) combine cell decomposition and primitive searching for the optimization of a whole building model. Henn et al. (2013) propose to use RANSAC and a supervised classification method to search simple building primitives in sparse lidar data (1.2 points/$m^2$). Fitting building primitives can be slow as the types and parameters of building primitives for each cell are determined by an exhaustive search. Furthermore, due to the complexity of building structures and inaccuracies in the available building footprints, exact decompositions that fit well with the roof shapes may be hard to generate.

With the further development of accuracy and density of point clouds obtained by laser scanning or dense image matching, roof faces can now be extracted more reliably from point clouds (Vosselman et al., 2004; Schnabel et al., 2007) and thereby can be taken as the basic unit for building modelling. By combining and intersecting the roof faces of basic shape, a polyhedral model can be reconstructed (Brunn and Weidner, 1997; Maas and Vosselman, 1999; Taillandier, 2005; Sohn et al., 2008; Sampath and Shan, 2010; Lafarge and Mallet, 2011). The topological relations between roof faces are very helpful in finding intersection lines, step edges, as well as the sub-shapes of the roofs. The roof topology graph is used to infer simple building primitives, like I, L, and U shaped primitives, which introduce geometric constraints for further improving models (Verma et al., 2006; Milde and Brenner, 2009; Oude Elberink and Vosselman, 2009). The topology graph is a powerful representation of the inner structure of building roofs and is easy to combine with prior knowledge. It is a low-level feature and gives hints about the structure to speed up the search. However, a roof topology graph may have errors if the point cloud segmentation fails because of outliers or low point densities on poorly reflecting surfaces (lidar) or textureless surfaces (image matching). The erroneous roof topology graph will result in incomplete interpretation and therefore a wrong model (Oude Elberink and Vosselman, 2009; Sampath and Shan, 2010).

### *2.2. (Sub-)Graph correction*

The spelling correction problem (Wagner and Fischer, 1974), also called the string-to-string problem, is similar to the graph correction problem we will introduce in this article. A detail review of string correction methods can be found in (Kukich, 1992). For a spelling correction problem, a full dictionary of correct strings