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An Automated Approach to the Generation of Structured Building Information Models from Unstructured 3d Point Cloud Scans

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Abstract
In this paper we present and evaluate an approach for the automatic generation of building models in IFC BIM format from unstructured Point Cloud scans, as they result from 3d-laser scans of buildings. While the actual measurement process is relatively fast, 85% of the overall time are spend on the interpretation and transformation of the resulting Point Cloud data into information, which can be used in architectural and engineering design workflows. Our approach to tackle this problem, is in contrast to existing ones which work on the levels of points, based on the detection of building elements, such as walls, ceilings, doors, windows, and spaces and the relation between these. We present use cases with our software prototype, evaluate the results, and discuss future work, that will bring the research further towards the aim to create automatically semantic links between the conception of building design in BIM and simulations with the build environment.

Keywords: BIM, Point Clouds, 3D Scanning, Evaluation, Computational Methods, Machine Learning, Semantic Web

1. Introduction
Today, the largest part of work conducted in the Architectural and Engineering Community (AEC) involves the existing building stock. In Europe, over 80% of all buildings are older than 25 years and in need for adaption to contemporary levels, especially regarding energy consumption[1]. Most of these buildings are bare of up to date documentation of their current state and need to be measured and documented in a way that allows building owners, architects, and engineers to assess the state and start their design and planning tasks.

3D laser scans of building structures are today quickly executed and precise which allows for an almost real-time monitoring of construction and provides an unprecedented base for further planning in the existing building stock. In industrialised countries, this task is executed increasingly [2,3,4] with tools and communication processes which follow the Building Information Modelling paradigm [5].
However, current BIM software and workflows are not ready to integrate the output of 3d scans, namely Point Clouds. Due to their oftentimes large size, handling point clouds is per se cumbersome. Additionally, they do not provide the structured information that AEC requires for planning. A transfer of the unstructured point clouds into machine-readable definitions of spaces and building elements (Fig.1) and a subsequent step of annotating this data with semantic information, such as materials, areas and connectivity of spaces is therefore indispensable. This post processing and BIM modeling currently requires expert knowledge and takes about 85% of the overall required time [6]. The challenge in the use of 3d scanning technologies has shifted from data acquisition to its interpretation and the subsequent reconstruction of a BIM model from it.

Figure 1: Example results on a point clouds with 67 scans. Left: point clouds after segmentation step; Right: reconstructed models; detected windows and doors are shown in grey. Most wall elements are faithfully reconstructed. Point Cloud: Højbro Plads, LE34 Denmark.

2. Current approaches and work environments for Laser Scan to BIM transformation

Current software tools are geared towards specialists and deal either exclusively with the registration and refinement of Point Cloud data, as those from 3D laser manufacturers, such as FARO Scene1 or Leica Cyclone2, focus on refinement, such as Bentley Pointtools3 or Autodesk ReCap4, or offer only a very limited degree of automatisation for the transformation of Point Clouds into CAD formats. Examples for the later are FARO Point Sense1, Clearedge Edge Wise5, Trimble Real Works6, Scalypso7, PointCap8.

In a research context, several methods for the reconstruction of digital 3D models from indoor point cloud measurements have recently been proposed. While these approaches are able to faithfully capture the overall geometry of a building, a plausible decomposition into parametric, globally interrelated, volumetric building elements – which is an important prerequisite for generating high-level BIM models – mostly remains an open challenge. Existing approaches represent walls,

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4 http://www.autodesk.com/products/recap-360/overview
5 http://faro-3d-software.com/CAD/Products/PointSense/index.php
6 http://www.clearedge3d.com/
8 http://www.scalypso.com/
9 http://www.pointcab-software.com/en/
floors and ceilings as sets of unconnected planar surfaces detected in the point cloud [7,8,9,10,11], or as collections of closed 3D boundaries of either the whole building [12], or separate rooms [13,14,15,16]. While some methods reconstruct volumetric walls [17], their thickness is defined manually instead of being estimated from the data which again requires manual intervention by the user as well as expert knowledge. To overcome the limitation of the previous approaches, our approach incorporates the representation of a building using BIM paradigms directly into the reconstruction process. The first steps towards this approach have been developed within the European FP7 research project DURAARK and published in [18]. This paper introduces the underlying approach shortly in the following chapter and thereafter focuses on the evaluation and application of the approach with real world datasets.

3. A fast workflow for the reconstruction of BIM from Point Clouds

Our automated BIM reconstruction method enriches a point cloud with a high semantic level of information about rooms, floors, ceilings, walls, doors, and windows, along with their relations. The input for this workflow is a Point Cloud from the 3d scan of the indoor of a building. This point cloud is provided in the e57 format and contains several overlapping laser scans. Note that the current limitation to this format is due to the prototypical character of our implementation, but not to fundamental reasons.

The automatic reconstruction process (Fig. 2) happens internally in several steps. In a first step, a coarse segmentation of the point cloud into separate rooms is generated, and clutter originating from points captured outside the building is removed. Infinitely long vertical wall candidate planes are generated by means of a RANSAC algorithm, which yields candidates for wall entities that are shared between rooms. The determination of a globally plausible configuration of connected wall elements is then posed as a graph labeling problem, which is solved using an energy minimization approach. Openings are detected and classified as either doors or windows by means of supervised learning.

Fig. 2: The automatic reconstruction process consists internally of several steps (from top left to bottom right): Input Point Cloud consisting of several scans, Coarse Segmentation, generation of infinitely long vertical wall candidate planes by means of a RANSAC algorithm, determination of a globally plausible configuration of
connected wall elements, solved using an energy minimization approach, final BIM model with detected openings, classified as doors and windows by means of supervised learning. Point Cloud: Gormsgade, LE34 Denmark.

An intermediate data structure of the reconstruction process is the representation of a building story as a halfedge graph in which faces are interiors of different rooms and edges are walls between adjacent rooms. The neighborhood relation of rooms is also directly contained in this structure, i.e. two rooms are neighboring if and only if they share a common edge. This representation allows for fast queries to which high-level building element (room, wall, floor, ceiling) a given 3D point belongs, which allows us to associate measured points to the aforementioned building elements. The tool hence not only creates a BIM model in IFC format, but also an RDF file which lists these associations of the building elements in the BIM file with points in the Point Cloud.

4. Evaluation

The evaluation of the toolset focused on three aspects:

1. The quality of the reconstructed IFC is evaluated regarding the needs of the stakeholders in terms of completeness, overall tolerances, and drawing conventions.
2. The precision of the reconstructed IFC is evaluated in terms of labeling of IFC elements (walls, doors, windows) and its dimensions in comparison with ‘ground truth’ models of real world data provided by stakeholders.
3. The relevance of the approach is evaluated through a comparison of the time which our reconstruction component needs for the reconstruction of IFC files, against the time needed for the same task by current state of the art workflows.

The evaluation took into consideration that the IFC reconstruction tool is a research prototype and has several known limitations. These include for example that the detected building elements are limited to walls, ceiling, floors, windows, doors and door opening directions, and that laser scans from different building stories, which lie on top of each other, can currently only be processed isolated from each other, such that connections like staircases are not reconstructed. Slight differences in the level of floor and ceiling are however detected and faithfully represented in the created BIM files. The focus of this evaluation activity are false and missing reconstructions of the currently detected architectural elements comprising walls, doors and windows.

4.1 Evaluation Method

The evaluation took place on the base of a dataset of 12 Point Cloud scans [Fig.3], which stem from the public DURAARK repository\textsuperscript{10} with currently 87 large point clouds from stakeholders. The selected 12 scans represent a wide range of architectural typologies, from residential to office layouts. Seven of the 12 point clouds are accompanied by IFC files, which were modelled by the stakeholders themselves on the base of the point cloud. For these we count the buildings elements algorithmically, for the others we get these quantities through a manual count. We consider this data to be the ‘Ground truth’.

We evaluate how well the underlying algorithm is working within the limits of its current state of development. As it is for example not able to detect columns we are not presenting datasets, which are predominantly consisting of these. We did however “stresstest” the tool with such datasets and

\textsuperscript{10} www.data.duraark.eu
found that the algorithm is to some extent able to reconstruct spatial topologies that are outside its capabilities. Figure 3 shows the “workarounds”, that the tool uses to generate geometrically working solutions - however on the costs of large statistical deviations in terms of the count of reconstructed versus actually existing elements.

Two tests were executed in order to evaluate the quality, precision and relevance of the results:

1) **Manual Comparison: Reconstructed IFC / Point Cloud.** A systematic manual comparison of the reconstructed IFC elements with the corresponding Point Clouds has been executed. We chose a manual approach through experts (Graduated Architects), as not all Point Clouds have a related IFC file, which could serve as Ground Truth. The manual inspection takes less time than manual modelling of the missing IFC files would. The comparison focuses on the level of building elements and checks for position and correct labeling of the reconstructed elements (wall, door, window). We allocate the reconstructed elements to one of two categories:
   - **False** - Elements, which have been detected at places, where no element exists. Elements which appear to be positioned or sized wrong (The tolerance by the human observer is here an approximate deviation of 50cm). Elements which have been wrongly labeled by the algorithm. This is for instance the case, when a window is labeled wrongly as a door.
   - **Correct** - Elements which are labelled correctly and are not considered to have the wrong position or size.

   We finally express the numeric relation of the amount of reconstructed elements to the one from the ‘Ground Truth’ in percentage [Fig.5].

2) **Statistic analysis** The aim of this investigation is to determine further parameters, which describe the quality of the reconstructions on a global level. For this we look at deviations between the seven ‘Ground Truth IFC files’ and the respective reconstructed IFCs. We find the amount of elements (walls, windows, doors) which have been reconstructed and compare these to the amounts in the ground truth and express the difference in percent. We investigate furthermore differences in the size of the reconstructed elements. For this we have a look at the overall area of elements as means to determine global deviations numerically. The area is a measure common to all investigated elements and allows to detect deviations in width and height in one go.

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Fig. 3: An overlay of the IFC reconstruction and Point Cloud of a NYC factory building, which consists mainly of columns and beams (left). The algorithm tries its best to interpret this despite the unknown architectural concept and reconstructs columns and beams as walls with extremely large doors, as shown on the right.
The evaluation activities have been conducted in respect to the affordances of a BIM in Level of Development (LOD) 1, as it is required by building owners and facility management. This LOD poses basic demands in terms of precision and range of elements (mainly walls, doors, windows, areas and relations of rooms). Our evaluation skips hence some potentially interesting investigations, as for instance whether a reconstructed wall element is aligned to the ‘Ground truth’ and whether it surfaces deviate. This case seems redundant in terms of the described use case for LOD1, which aims at highest possible abstraction. It furthermore points at limitations of the BIM paradigm, where a wall is by default a straight and vertical entity. The representation of e.g. slightly curved or partially bulging walls, is in any way a challenge for BIM.

Fig. 4: Overview of the 12 evaluated datasets with highlighted deviations for walls, doors and windows (red - falsely labeled and wrongly detected, magenta - not reconstructed elements, blue - deviating in area or position).

4.2 Evaluation Results
The processing time to generate IFC files from large point clouds with the IFC reconstruction tool as well as the comparison of the generated IFC files against the original point clouds and the gathered IFC groundtruth show that the reconstructed IFC’s are in terms of overall completeness and tolerance very close to the requirements of the stakeholders. The related datasets of the evaluation can be found in [19]. A detailed analysis in terms of Relevance and Quality & Precision is provided in the following section.

4.2.1 Evaluation - Relevance of approach towards stakeholders
A tool is relevant to stakeholders if it is more efficient than existing ones, while providing the same or better output quality. The bottleneck of current Point Cloud-to-BIM approaches has been identified in the modeling part [6], where 85% of the overall time is consumed. In order to verify these statement we asked an expert to model a BIM file manually from the ZESO Nygade dataset. This process took 6 hrs. The same task has been performed by the presented tool within 6min 54sec. This points at a high competitiveness of the tool, even if some manual correction of the automatically generated results has to be added to the required time. The time for the automated reconstructions of other datasets has been measured for comparison [Fig. 5].
4.2 Evaluation of Quality and Precision of approach

This section describes the results of the evaluation activities as described in 4.1.

4.2.1 Wall Detection

The manual comparison between wall reconstructions and the Point Cloud shows that almost all walls are reconstructed [Fig. 5]. The amount of False Wall Reconstructions is with an average of 5.5% relatively low. We determine, that the majority of the deviations originate from columns and beams being reconstructed as walls [Fig. 3] or very thick walls being reconstructed as multiple wall elements [Fig. 6].

The statistical analysis of differences in the reconstructed wall elements and the ‘ground truth’ in the 7 datasets, which have an expert modelled IFC file, shows that in average 30.1% more wall elements are reconstructed. The tool generates in general more wall segments, than a human modeller would. The total area of Wall Reconstructions is in average 6.7% smaller than the ‘ground truth’, and the average wall element size is 25.8% smaller, most likely due to in general oversized window and door elements. A further cause is that the tool can at present not reconstruct exterior walls faithfully, as exterior scans are currently not be taken into account.

Fig. 5: Results of the manual evaluation of the automatic IFC reconstruction in terms of processing time and quality of the output.
Fig. 6: Thick walls reconstructed as multiple wall elements in the CITADesign Museum Copenhagen dataset.

The larger amount of walls and smaller average size of wall elements indicates, that the reconstruction tool segments walls into smaller pieces than what is present in the 'ground truth’. An investigation of floor and roof slabs, shows for instance, that these are reconstructed by the tool as one slab per room, while they are in general modelled by stakeholders in the 'ground truth IFC’ as one slab per level. Both approaches are principally right, but the modelling convention of stakeholders seems to usually ask for a continuous slab across a building level.

4.2.1 Door & Window Detection

The manual comparison shows, that the detection rate of doors and windows from the point clouds is good: in average 91.2% of the doors and 72.8% of the windows in the 'ground truth’ are detected. [Fig. 5]. Both types of elements are detected with an algorithm based on supervised machine learning. We find, that the algorithm detects in general a high percentage of openings (windows and doors), but labels them often wrongly (windows as doors and vice versa).

Looking only at the amount of detected doors we find that the not detected doors often originate from poor scanning practice: doors have simply been closed at the time of scanning (e.g. Statbyg Rislekka) and hence went undetected by the algorithm. Another reason for False Door Reconstructions is that openings in walls, columns and beams are described as walls with doors [Fig. 3].

Furthermore, the algorithm tends to label window openings as doors [Fig. 7, 8]. This results in a higher count of elements labeled as doors, than in the ground truth, and obviously a large amount (39.5%) of falsely labeled and reconstructed elements. However even within the scan with the most amount of wrongly labeled elements (KADK Building 72 s) all doors in the ground truth are detected.

![Fig. 7: Interior view of dataset Haus 30 by Plan 3D/Berlin where windows are wrongly labeled (red) as doors.](image1)

![Fig. 8: Overview of Plan3D Haus30 with annotations. The majority of red labels point at windows, which are wrongly declared as doors by the IFC reconstruction tool.](image2)

The statistical analysis of differences between reconstructed doors and the ‘ground Truth IFC files’ shows, that in average 50% more elements are reconstructed. The total area of the reconstructed elements is 192.2% larger and the average element area is 95.6% larger. As previously mentioned this is mainly due to wrongly labeled door reconstructions. A very different picture emerges when these wrongly labeled door reconstructions are not taken into account. Then the average amount of doors is 14.6% smaller, the total area is 6.3% smaller and the average element area is 9.8% larger.
This corresponds with the low amount of not reconstructed doors described earlier and indicates again, that a big amount of windows are wrongly labeled as doors.

The numbers from the statistical analysis show furthermore, that the correctly reconstructed doors are in general slightly over dimensioned [Fig 9]. In order to quantify this we compare the width and height of all reconstructed doors with those from 33 IFC ‘real world’ IFC models from the DURAARK repository. The plateaus in the histograms from this analysis [Fig. 10] show, that most of the doors in the repository have actually a similar width (700mm, 900mm or 1000mm) and an almost uniform height (2100mm). A future version of the IFC reconstruction tool might use an heuristic approach in order to eliminate or indicate door candidates, which are outside the norm.

6. Conclusion

The developed tool is able to fill the gap of building documentation for legacy buildings. The produced BIM models can provide a simple yet important base for retrofitting or analysis purposes. The outcome of the tool are IFC models on a rudimentary level of Detail (LOD 1). The evaluation of the first prototype of this fully automated approach on a large set 3d-scanned buildings from stakeholders indicates a high robustness and reliability with around 87.7% of all wall, windows and door elements in the point clouds being detected. The largest amount of errors stems from the incorrect labelling of windows as doors. The amount of not reconstructed elements is relatively small and we do not see this as a major obstacle for the tool to meet expectations of stakeholders.

The tool is in a prototypical state and future work should expand the range of detected building elements (e.g. columns, beams and outer walls) and spatial situations (slanted ceilings, free standing wall elements, multistorey building). Future work might as well include the detection, classification and naming of elements based on a set of families of BIM elements and BIM standards provided by users.

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References


