From Point Clouds to Definitions of Architectural Space

Potentials of Automated Extraction of Semantic Information from Point Clouds for the Building Profession

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Regarding interior building topology as an important aspect in building design and management, several approaches to indoor point cloud structuring have been introduced recently. Apart from a high-level semantic segmentation of the formerly unstructured point clouds into stories and rooms, these methods additionally allow the extraction of attributed graphs in which nodes represent rooms (including room properties like area or height), and edges represent connections between rooms (doors or staircases) or indicate neighborhood relationships (separation by walls). In this paper, we investigate possible applications of these approaches in architectural design and building management and comment on the possible benefits for the building profession. While contemporary practice of spatial arrangement is predominantly based on the manual iteration of spatial topologies, we show that the segmentation of buildings in spaces along with the untraditional more abstract graph-based representations can be used for design, management and navigation within building structures.

Keywords: *3D Scanning, Point Cloud Processing, BIM, Facility Management, Space Syntax*

INTRODUCTION

Indoor 3D point cloud scans have become increasingly important in architecture, as they enable a three-dimensional documentation of buildings for which no CAD models exist as well as documentation of differences between built architecture and the original CAD plans. Having faster and easier access to 3D documentation of building structures is important, as today over 80% of all buildings in Europe are older than 25 years and in need of adaption to contemporary levels with respect to usability, functional requirements and energy performance.

The effort needed in order to capture existing building stock is hereby decreasing, as the constant evolution of 3D scanning technologies increases the speed of scanning, the quality and density of the point cloud, while error margins and the amount of manual labour needed is reduced (Hichri et al. 2013). Capturing the existing building stock has also been facilitated by certain recent developments: 3D scanning devices (1) have become increasingly autonomous and can prospectively scan complete buildings without user interaction (e.g. ScanBot by Faro Labs), (2) have become able to scan hard-to-reach areas of architectural structures, like e.g. the ScanCopter by Faro and 4D-IT, and (3) have been enabled to scan complete structures ultra-fast in walking speed, see e.g. the ZEB1 developed by CSIRO Autonomous Systems Lab. (Fig.: 1)

Figure 1
Recent developments in 3d registration technique: Faro Labs ScanCoptor , Faro Labs ScanBot and CSIRO ZEB1 (From Left to Right). Images courtesy by FARO and CSIRO

While scanning itself is becoming seemingly faster, a considerable effort is needed to post-process the acquired data, as in contrast to highly structured and semantically enriched Building Information Models, point clouds are completely unstructured and contain no semantics at all.

Due to their unstructured nature, it is virtually impossible to define meaningful parts in the raw data, e.g. rooms or stories. These definitions are yet imperative for further architectural planning efforts, as in applications for management and navigation within building facilities (FM tools) and are as well needed for targeted (textual) search, manipulation, measurement takings, and efficient rendering. This forces architects and construction companies to manually generate 3D Building Information Modeling overlays of the point cloud and additional metadata information. Due to the large amount of manual post-processing necessary, the advantages that come along with the digital capturing devices are in practice to a bigger part lost again.

Computational approaches might minimize the efforts needed to create architectural data from point clouds.

Several approaches to indoor point cloud structuring have been introduced recently, see e.g. (Ochmann et al. 2014). Apart from a high-level semantic segmentation of the formerly unstructured point clouds into stories and rooms, these methods additionally allow the extraction of attributed graphs in which nodes represent rooms (including room properties like area or height), and edges represent connections between rooms (doors or staircases) or indicate neighborhood relationships (separation by walls). This semantic approach to the structuring of point cloud data challenges the traditional representation of buildings through mass, as wall elements, ceilings and floors, as it results in none of them. It provides an information rich interior building topology, that might on a second view be an important aspect for a future Building Information Modelling approach towards architectural design and building management and create benefits for the Architectural and Engineering Community (AEC).

While contemporary practice of spatial arrangement is predominantly based on the manual iteration of spatial topologies, this paper shows the potential of semantically rich graph-based representations of spaces found in point clouds for design, management and navigation within building structures.

RELATED WORK

A prominent use of definitions of spaces in architectural planning is in Space Syntax. Within this context bottom-up design strategies for buildings are proposed that generate the topology of spaces based on their preprogrammed relations and functions in an iterative process that evaluates the internal organization of spatial entities as their relation to a building shape. These methods can as well take the cognitive needs of designers into account as they are informed by the perception of information and knowledge and how it is acquired, stored and processed. William Mitchell describes in his "Logic of Architecture" (Mitchell 1992), how such descriptions of building structures may be formalized.

(Deleuran et al. 2013) further argue that traditional modes of representation are not able to capture cognitive and organizational properties of space, such as circulation networks. His approach is based on a domain model based on 2D floorplans from which a graph based formalized mode of architectural representation for mapping, abstracting and analyzing is extracted. This is used to find the space's resilience to security and safety concerns in building design and layout planning.

The knowledge of spatial relations from previous projects can as well directly support architectural planning. (Langenhan et al. 2013) develops a system for sketch-based queries by topological substructures of buildings in a database containing precalculated so-called "semantic fingerprints" of existing spatial solutions.

The topological information can be extracted from 2D (Deleuran et al. 2013) or low-level 3D CAD representations of buildings, from which Wessel et al. automatically extract 2D plans (Wessel et al. 2008). From this they generate room connectivity graphs as a topological representation of architectural storeys for easier search and retrieval of CAD building models. (Langenhan et al. 2013) uses the spatial definition of spaces (ENTITY IfcSpace) in IFC files. These are very common in current practice and represent an area or bounded volume. According to the IAI definition [1], a space represents an area or volume bounded actually or theoretically. Spaces are here areas or volumes that provide for certain functions in a building. In IFC files a space is associated to a building storey (or a site, in case of exterior spaces) which describes its elevation (+flooring offset). In case of volume, the height can be provided by elevation of bottom of suspended ceiling. Geometrically, spaces can be represented by 2D curves or a 3D body. The body can be an extrusion of a footprint, it can be subjected to a Boolean expression or it can be a multifaceted boundary representation (BRep). In contemporary practice spaces are mostly used to calculate areas, denote functions of rooms in 2D representations, while the 3D BReps are used for energy simulation, often via gbXML export.

The IFC definition of spaces is however imprecise as they can refer to huge variety of spaces, as actual rooms, outdoor spaces, virtual delimitation of spaces and can as well overlay (Figure 2). If used for the planning within existing building stock, the spatial definition provided in IFC files necessitate hence a verification with the physical reality.

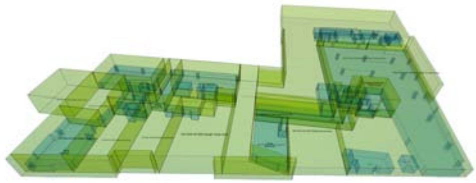


Figure 2
An IFC compliant BIM model, that shows overlapping spatial definitions.Courtesy of NCC, Carlsby IFC model in Solibri Model Viewer.

APPROACH

As shown above, design processes can greatly benefit from spatial definitions. However, existing definitions are usually outdated or even missing for existing building stock. We tackle this problem through the algorithmic extraction of semantic descriptions directly from point cloud scans of building interiors. If implemented into the architectural toolset the amount of manual labor by specialists is reduced greatly.

The proposed method for room segmentation and opening detection is described in detail in (Ochmann-GRAPP, 2014). We will summarize the approach below. The identification of meaningful structures and features within Point Clouds is non trivial, far from solved and part of ongoing research. In contrast to other methods which focus on the reconstruction of boundary representations (e.g. Turner et al. 2014, Oesau et al. 2013, Xiao et al 2012, Mura et al. 2013), segmentation of objects within rooms (e.g. Kim et al. 2012, Nan et al. 2012, Shao et al.

2012), or work on different kinds of representations (e.g. Ahmed et al. 2013, Langenhan et al. 2013, Wessel et al. 2008), the proposed method works purely on point cloud data and yields a concise description of a building's topology.

Step 1: Initial Room Labeling

The starting point of the segmentation process are indoor point cloud scans of a building which have been registered (i.e. spatially aligned) in a common coordinate system; the registration is usually done by the scanner software. Clutter outside of the building (e.g. surroundings scanned through windows) is removed beforehand. In addition to reducing computational complexity this also removes outlier points for which the room labeling described below is not meaningful. This step is currently done manually by performing a coarse selection of the region of interest, however we are experimenting with techniques to automate the process of detecting and removing such outlier points. An example input point cloud is depicted in Figure 3. The goal is to find a labeling of all points such that each point is assigned to one of the rooms of the building which yields a semantically meaningful segmentation of the cloud. As an initialization for this labeling, we start with n different labels where n is the number of scanning positions and each point is labeled with the scanning position from which it originates. Subsequently, if a particular room has been scanned from more than one position, the corresponding labels are merged to a common label; this step is currently done manually using a graphical user interface. We are then left with m different labels where m is the number of rooms in the building. This initial "guess" for the room labeling is shown in Figure 4. Obviously, this initial labeling is ambiguous in regions in which multiple scans overlap.

Figure 3
Initial colored pointcloud

Figure 4
Initial rough point-to-space assignments. The affiliations of points to spaces are color-coded.

Step 2: Refinement of Room Labeling

The initial room labeling is subsequently refined using a diffusion process of room labels between points which is governed by mutual visibility between them. The underlying idea is that most points that can be "seen" from a certain point p tendentially have the correct label and it thus reasonable to take the average labeling of visible points as a new, improved guess for the labeling of p. This process is iterated a few times, allowing the diffusion to take place between points which are not directly visible from each other but only indirectly (e.g. around a corner or if a region is hidden behind a piece of furniture). Figure 5 shows an example of the room labeling after the refinement step.

Figure 5
Final segmentation - space labeling after refinement.

Figure 6
Automatically recognized space neighborhood graphs

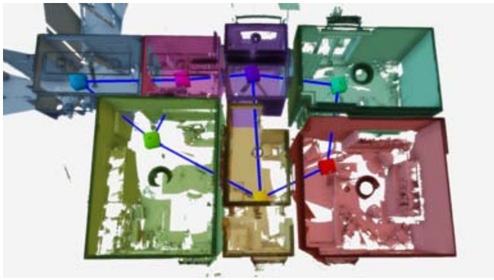
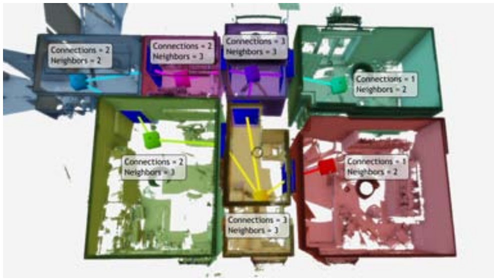


Figure 7
Space connectivity graphs including captions showing the number of openings and neighbors.



Step 3: Detection of Room Neighborhood and Openings

Based on the segmentation of the point cloud data into rooms, the room neighborhood relation is determined by automatically searching for wall structures separating adjacent rooms. Wall structures are sought by detecting pairs of planar structures (i.e. the scanned surfaces of the walls) fulfilling certain constraints (e.g. they shall are close enough, have plane normals pointing away from each other and possess different room labels). The resulting room neighborhood is depicted in Figure 6. While this relation already yields valuable information, e.g. for performing an analysis of sound propagation between adjacent rooms, openings between neighboring rooms are detected in a subsequent step. Each pair of neighboring planar structures is tested for intersections with a certain subset of rays between scanner positions and the measured points, namely those rays whose origins (i.e. scanner position) are located in a different room than the corresponding measured points. These sets of intersection points are then used to approximate the geometry of openings (e.g. doors, vertical openings for staircases). Figure 7 shows the detected door connections in the example dataset; Figure 8 also includes captions showing the number of openings and neighbors for each room. A limitation of this approach is that a sufficient amount of overlap and thus rays shot through openings between adjacent rooms is required in order to be able to detect openings. However, such overlaps are usually required anyway in order to perform the (semi-)automatic alignment of the scans to each other in the scanner software.

Step 4: Export of Data

For demonstrating the usage of the extracted meta-information for the generation of IFC representations of a building we have developed a prototypical tool for the generation of IFC files from the processed point cloud data. Although our long-term goal is to enable (semi-)automatic generation of rich IFC files including floor, ceiling and wall structures, as well as openings, we have for now focused on the export of "IfcSpace" entities as a first step towards this goal. Following the definition of the IFC 2x3 standard, IfcSpace entities are commonly used for representing an area or volume within a building, bounded actually or theoretically. In our approach, we generate one 2.5D IfcSpace for each room label present in the point cloud. Here, 2.5D means that each space consists of a closed polygonal footprint together with a height of the respective space. Starting with a point cloud in which point labels indicate the affiliation to a certain room, the problem of generating IfcSpace

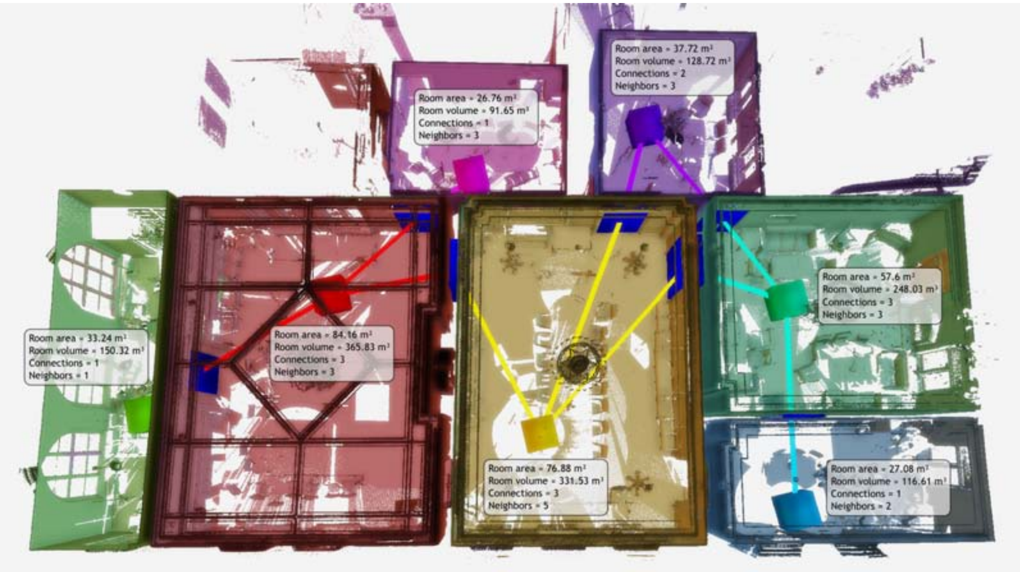


Figure 8
An example for space segmentation and determination of room relationships. 3D scan with overlay of the room connectivity graph and all further information extracted from the 3D scan. 3D scan courtesy by Statsbyg Norway3D

entities consists of structuring the scene into a disjoint set of polyhedra, each one representing one room. The challenge here is twofold: On the one hand, room borders must be sufficiently regularized such that outliers and noise do not cause them to become jagged. On the other hand, systematic deviations from the broader wall structure should be faithfully captured even if they are small. This trade-off can be formalized as an optimization problem.

Our approach to solving this problem is coarsely based on ideas by (Schnabel et al. 2009) who propose a primitive-driven mesh reconstruction method from point cloud data and (Mura et al. 2013) who generate a two-dimensional cell complex from extracted vertical wall planes and subsequently perform a room labeling by means of diffusion maps in an spectral embedding of the cell complex. For assigning room labels to each of the resulting cells, we use a multi-label optimization algorithm by (Boykov et al. 2001). This yields a regularized labeling of the cells while trying to adhere to the detected wall surfaces where possible. This adherence to detected planes is done by penalizing usage of cell borders which do not belong to detected planar structures as separating lines between differently labeled cells. After the cells have been assigned their labels, adjacent cells with the same label are merged such that we obtain labeled, polygonal regions for each room. These regions are subsequently exported as an IFC file containing one IfcSpace entity for each region. Figure 9 shows an example for the resulting IFC.

RESULT OF APPROACH

The final result of the proposed method is a semantically meaningful assignment of all points to the building's rooms as well as a concise description of room neighborhoods and connections between adjacent rooms. In addition to providing a better insight into even large-scale datasets (e.g. by enabling hiding or highlighting of certain areas of the building for inspection), it also provides concise, higher-level information about the building's topology. Further structuring of the obtained information, for instance a grouping of rooms into storeys as well as a further segmentation of rooms into objects contained within them, may be performed as detailed in (Ochmann-3DOR, 2014) which also demonstrates the usage of the extracted room connectivity graphs for performing searches of building sub-structures.

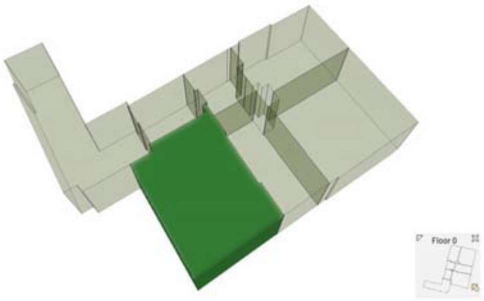


Figure 9
Example for an IFC extracted from the point cloud shown in Figure 2-7. One of the IfcSpaces is highlighted.

AREAS OF APPLICATION IN BUILDING PRACTICE

Already basic tasks in Facilitiy Management (FM) as the accounting of areas and volumes require a semantic understanding of spatial structures. As introduced beforehand, this is even more necessary for the integration of existing building structures into FM processes, which is seemingly understood by architects and building owners as a constant monitoring and adaptation sequence (Graf et al. 2011, Gu et al. 2013). In practice, design extends into the realm of building operation, as the continuous optimisation of buildings and their adaptation to upcoming needs require design decisions. This requires the semantic linkage of spatial hierarchies and geometries to other existing information on the building and an ongoing process of updating this data. A growing set of FM software, as Dalux [2], Archidata [3], Gralund Mangaer [4], Rambyg [5], ActiveFacility [6], supports the continuous collection of data related to state and changes in buildings and provides connection to other building relevant systems, as energy monitoring systems. However, today most FM systems do not contain actual 3D geometry or a sense of their semantic relations.

The approach described in this paper is to provide a better understanding of existing buildings and grants a new base to the architectural design of retrofitting and user-oriented space management according to ergonomic principles:

- Performance based programming of space - As real-world architecture has significant semantic structure, the knowledge of spatial relations allows to engage a performance based design of spaces. An example of this approach is the consideration of the impact of sound emitting spaces (entrance halls, function rooms, ..) on neighboring spaces, which tend to be more quiet, e.g. offices. The room neighborhood graph, as depicted in Figure 5, is suitable as basis for the allocation of spaces or for the calculation noise-reducing actions, which can be further assessed through simple rules or simulations (Cavanaugh et al. 1999). This provides crucial feedback for the optimal positioning of spaces according to their sensitivity towards noise.

- *Planning of building retrofitting* - An essential part of contemporary planning of builiding retrofitting is concerned with energy usage. Energy simulation (Diaz-Vilarino et al. 2014) requires however data on the volume of spaces, their orientation and relation to each other. The further knowledge of current and future use of spaces and other semantic data helps to verify design decisions regarding spatial distribution of program, as the dimensioning of technical appliances.

- *Access management* is an application widely used in FM tools, and requires information on spatial connections as well as on different properties like floor area or door sizes. Figure 8 depicts a automatically extracted room connectivity graph with attributed nodes and edges including semantic information needed for planning and simulation of spatial programs. Graph and properties can be used as basis and for enrichment of FM information to facilitate access management.

- *Assessment of security and safety in building design* is an emerging field (Deleuran et al., 2013) and requires information on spatial relations, connectivity occupation and distances for the optimization of emergency routes as well as the assessment of terrorist threads.
- *Mobile Navigation systems* for outdoor use are standard applications on mobile phones. These applications are seemingly entering navigation in indoor spaces and require for this information about buildings that extend spatial and graphical aspects. In particular, the ontological structure of buildings have to be defined (Diaz-Vilarino et al. 2014). This information is not readily available from existing CAD drawings, nor from laser scans. The approach described in this paper is resulting in semantic descriptions, that have the potential to deliver data in the Node-Relation-Structure (NRS) required for indoor mobile navigation systems. (Lee et al. 2005). These geospatial formats are undergoing standardisation efforts at the moment (ISO-CD 17438-1) and out an emphasis on the compatibility to the Industrial Foundation Class Format (IFC).
- *Programming of space and distribution of functions* - The detected distances between spaces, can be of benefit for the planning and optimisation of workflows and the necessary pathways in existing buildings. Recent approaches extend the until now applied shortest path algorithms, as they take an extended three-dimensional dataset with additional metadata into account (Ya-Hong et al. 2013). An application for such way planning are hospitals, which are characterised by many overlaying workflows. The graphs detected through the approach described in this apper can help to find the best arrangement of spaces with the shortest routes for users (Fig 10).

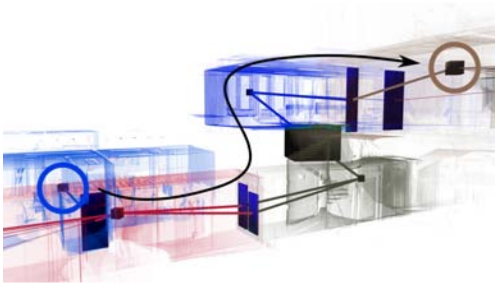


Figure 10
A graph is used to find a path between an office space (identified through algorithmically detetced office chair- red) and sanitary area (identified through algorithmically detected sink- red)

EVALUATION

The created spatial definitions in are fully compliant with the IFC standard and tests show that the most common IFC viewers (Solibri Model Checker) and BIM modelling tools (Revit) import and render the spaces correctly, using their individual approaches to the display of spaces (Solibri: 3d representation of spaces, Revit 2d representation of spaces (Fig. 11)). Metadata detected in the point clouds or additionally entered in the tool described here, as names of spaces, is imported correctly.

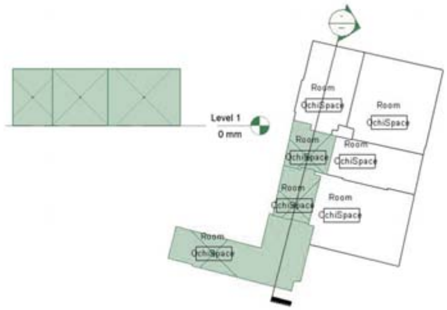
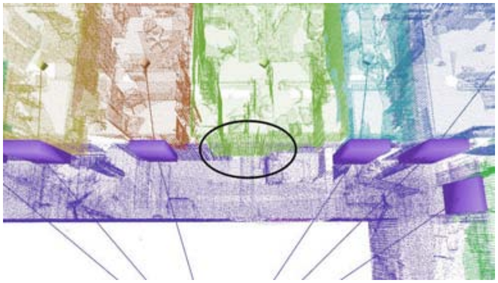


Figure 11
Two dimensional display of the imported IFC file in Autodesk Revit

The detection of meaningful architectural information in point cloud data remains a challenge. One particular difficulty is the sheer size of the datasets. The point clouds of a single building may easily con-

Figure 12
A case of a missed door in a dataset from Risløkka trafikkstasjon, Oslo. The reason for this is that the overlap between the scans of the "yellow" and "blue" rooms is not large enough due to a closed door from the side of the "yellow" room and sharp scanning angles from the side of the "blue" room.

sist of tens of gigabytes of data which usually renders processing of the data in core memory infeasible. However, as the proposed method does not require the full resolution of the point cloud for performing the computations, downsampled versions of the datasets may be used which fit into main memory and also allow fast, parallel computation of visibilities between points on graphics cards. In our experiments, it sufficed to retain (at most) one point per voxel of 2 cm side length. Other challenges, especially when dealing with real-world datasets of inhabited buildings, are highly cluttered rooms and complex, non-convex room shapes. The proposed method is able to deal even with challenging cases due to the formulation as a diffusion process which is able to gradually refine the initial labeling despite occluded or non-convex regions. In addition to synthetic datasets, the method was tested on several real-world datasets from different scan providers on which it yielded satisfactory results. One limitation of our method for the detection of openings between rooms is that it requires the openings to be (at least partially) unobstructed during the scanning process (in particular doors need to be standing open), and that a sufficient overlap between scans of different rooms exists; Figure 12 shows a failure case of the opening detection. In general, assuming the availability of overlaps between rooms is not a hard constraint due to the fact that such overlaps are usually necessary for performing the registration of indoor point cloud scans. Another current limitation is that we currently use only planes to approximate walls which limits the applicability in the presence of curved walls.



CONCLUSION

The described algorithmic methods demonstrate the benefits that a semantic linkage of real world spaces and their representation in BIM can provide. Especially planning processes in existing building mass benefit, as the generated room connectivity graph can be queried on the level of the individual spaces (volume and area) as on the level of spatial topology. This will provide stakeholders a mean to query their models in a project specific way through rule-based algorithms for user-oriented space management according to ergonomic principles and help them to identify opportunities for better design concepts. Future work will have to improve the underlying algorithms, as new opportunities might arise through the semantic detection of objects in spaces. The presented methods can however be seen as a first step into the automated generation of BIM models from 3D laserscans.

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