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Bachelor Thesis

Automating Scan-to-BIM for Telecom Site Planning

A Comparative Analysis and Case Study

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Declaration of Originality

I hereby declare that the written work I have submitted entitled

Automating Scan-to-BIM for Telecom Site Planning

is original work which I alone have authored and which is written in my own words.[1]

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Preface

This thesis was developed as part of my bachelor's degree in geospatial engineering. Since I enjoy translating scientific findings into practical applications, I sought an industry-related project for my research.

TODO: Finish this paragraph

Jeffrey Leisi
Zurich, 2025

Abstract

- **Introduction to the Topic**
- **Research Objective**
- **Methodology**
- **Results**
- **Conclusion and Impact**

Keywords

BIM, Scan-to-BIM, telecommunications, automation, point cloud processing

Contents

Acronyms and Abbreviations

ETH	Eidgenössische Technische Hochschule
D-BAUG	Departement Bau, Umwelt und Geomatik (depatement of ETH)
IBI	Institut für Bau- und Infrastrukturmanagement (institute of D-BAUG)
CEA	Circular Engineering for Architecture (research group at IBI)
BIM	Building Information Modeling

Chapter 1

Introduction

1.1 Background and Motivation

The construction industry is one of the largest economic sectors, yet its productivity has stagnated for decades. In the two decades from 1995 to 2015, its productivity grew by only 1%, far below the global economy's average of 2.8%. One of the reasons cited is the low level of automation [1].

Until the turn of the millennium, construction planning had been largely digitized, primarily through the use of Computer-Aided Design (CAD) for creating construction drawings. This represented an evolutionary innovation, optimizing conventional planning methods. Manual drafting on the drawing board was replaced by manual drafting on the computer, while the individual work steps remained largely the same. In conventional planning, a real object is inductively represented by individual two-dimensional drawings (e.g., floor plan, section, detail). These drawings are often stored as isolated files (e.g., DWG, DXF) and are neither geometrically nor semantically linked. Any changes to the real object must be manually updated in all drawings. [2]

At the turn of the millennium, Building Information Modeling (BIM) began to gain traction. It represented a disruptive innovation that fundamentally changed previous workflows. In model-based planning, a three-dimensional model is created as a digital representation of the real object. The two-dimensional drawings are then deductively derived from the model. The model is stored as a unified file (e.g., IFC) and contains both geometry and semantics. Any changes made to the model are automatically reflected in all drawings. [2]

Scandinavian countries and the United Kingdom have taken leading roles in the implementation of BIM. However, integrating the technology in Switzerland has proven challenging. By 2021, only 20% of Swiss construction companies had adopted BIM, compared to 70% in Germany and 80% in the UK. This places Switzerland slightly above the European average. [3]. Among the factors contributing to this slow adoption are the fragmented nature of the construction industry and high competitive pressure, which led smaller companies, in particular, to shy away from the initially high investment costs. [4].

The Swiss telecommunications industry has recognized the potential of model-based planning. While the traditional construction industry typically focuses on large, individual construction projects, the telecommunications sector operates with a high volume of smaller, standardized projects, involving the installation of mobile radio systems on existing buildings. For the planning of such projects, the respective building should be efficiently converted into a digital model.

Various approaches have been developed for converting buildings into digital models using reality capture:

- **Scan-to-Mesh:** Scan-to-Mesh generates a purely geometric surface model (mesh). This model often consists of thousands of small triangles that are not logically structured. It contains no semantic information such as object classes or component properties and primarily serves for visualization and geospatial analysis. While the generation is relatively quick, subsequent editing or structuring is labor-intensive.

  Analogy: Scan-to-GIS is comparable to scanning a text document as an image. The content is visible, but it is neither structured nor editable.

- **Scan-to-BIM:** Scan-to-BIM involves creating a BIM model for use in BIM software. This model consists of logically structured building components and contains semantic information. It is used for detailed planning and documentation of buildings. Generation is more complex than with Scan-to-GIS, as the models must exhibit higher geometric accuracy and semantic structure. For site planning, building plans must be created, requiring editability.

  Analogy: Scan-to-BIM is akin to typing the text document into a word processing program. While this is more labor-intensive, it allows for targeted further processing and analysis.

1.2 Research Gap

Scan-to-BIM has been intensively researched in recent years **rochaSurveyScantoBIMPractices2021**. The literature found seems to focus primarily on the traditional construction sector and the documentation of historical buildings. No publications specifically addressing site planning could be found. For site planning, interior structures are not required, and the facade geometry can be highly generalized. Compared to the requirements of the classical construction industry, the conditions are simpler, allowing for a higher degree of automation, which has only been found in Scan-to-Mesh processes so far. The subject area lies at the intersection of three disciplines: telecommunications, geomatics, and construction (see Fig. 1.1). Due to this interdisciplinary orientation and high specialization, it is assumed that it has hardly been scientifically investigated so far.

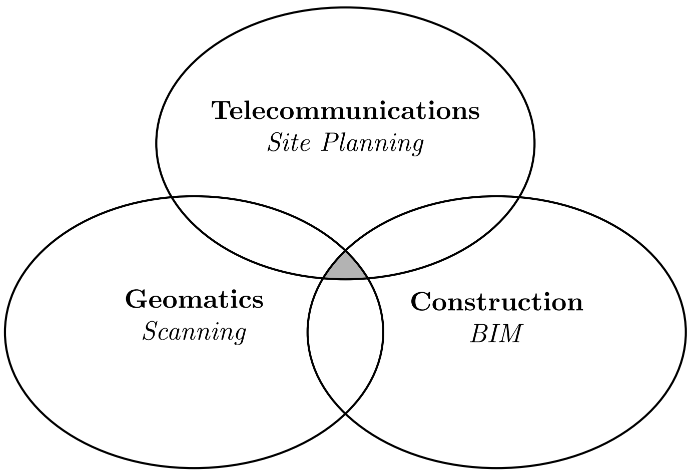


Figure 1.1: Intersection of Disciplines

1.3 Research Objectives

The goal of this work is to develop an automated procedure specifically tailored to the requirements of site planning in the telecommunications industry. A simplified modeling process, limited to exterior structures, will be developed. A particular focus is placed on high automation to enable efficient and scalable implementation in the planning process. This leads to the following research questions:

- **Main Question:** How can Scan-to-BIM be automated for telecom rooftop site planning?
  - **Sub-Question 1:** Which steps of Scan-to-BIM can be automated for rooftop site planning?
  - **Sub-Question 2:** Which tools enable rooftop Scan-to-BIM automation?

To answer the research questions, the "Design Science Research Methodology" is employed. Initially, existing Scan-to-BIM workflows are examined through a literature review. These workflows are then iteratively adapted to the needs of site planning into a custom framework. From this, a toolchain (Python, Dynamo, Revit) is derived and validated using a case study. The final outcome is a procedure capable of fully automatically extracting the characteristic building geometry and semantics from a point cloud and generating a BIM model based on this information.

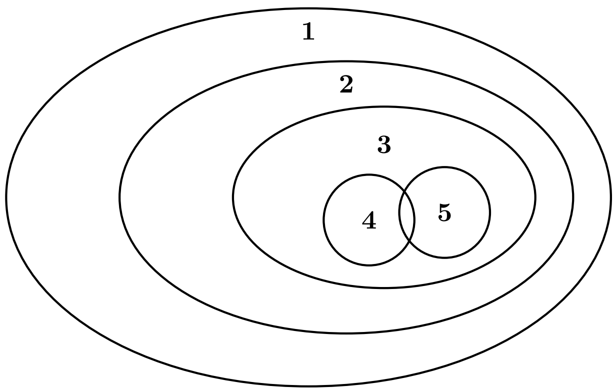
Chapter 2

Literature Review

2.1 Cell Site Planning

Mobile communications is a subfield of telecommunications (see 2.1) that generally deals with the wireless transmission of voice and data and allows receivers or transmitters to move freely (WLAN, Bluetooth, satellite communication, ...). [5]. **Cellular communications** is a subfield of this, in which **cellular networks** are used [6]. A cellular network consists of several radio cells. The planning of these networks is called **cellular planning**. Within this field, different disciplines have developed:

- **Radio Network Planning (RNP):** Radio network planning has an electrical engineering focus and determines where radio cells should be located, how the signal is distributed, how many users can be connected simultaneously, and how interference can be avoided. [7], [8].
- **Cell Site Planning:** Cell site planning has a structural engineering focus and refers to the identification and structural implementation of a physical site within the perimeter defined by radio network planning [9].



1 - Telecommunications
2 - Mobile Communications
3 - Cellular Communications
4 - Radio Network Planning
5 - Cell Site Planning

Figure 2.1: Telecommunications Hierarchy

This work focuses on cell site planning. For the literature analysis, two general works on mobile communications from Springer [6], [10] as well as three papers listed under cell site planning [11], [12], [13] were consulted. It was found that mainly electrical engineering topics are addressed. One possible explanation could be that electrical engineering areas such as radio technology and signal processing have a high technical depth and are therefore extensively researched. As a result, these areas have been strongly standardized internationally (ITU, ETSI, 3GPP). Structural topics, on the other hand, depend more on local conditions, which are regulated by practical guidelines. For this purpose, a report commissioned by the Federal Council "Sustainable Mobile Network" was consulted [14].

The following section summarizes key findings of the literature analysis. In the field of cell site planning, the terminology of the Swiss mobile communications industry is used.

2.1.1 International Status

Worldwide, mobile data traffic is increasing exponentially [15]. Until around 2020, traffic doubled about every two years. Annual growth rates of an average of 19 % are still forecast for the period until 2030. Currently, 34 % of mobile data traffic is handled via 5G networks. By 2030, this share is expected to increase to 80 %.

The increase has been significantly driven by video streaming with ever higher screen resolutions (4K, 8K), which now accounts for 74 % of mobile data traffic [15]. The main drivers of future growth are seen particularly in the areas of autonomous driving, Extended Reality, Industry 4.0, and generative AI. Fixed Wireless Access (FWA) will become increasingly important and account for a significant share of the traffic by 2030 with 36 %. Stationary devices (e.g., computers) are supplied with a fixed broadband connection via a CPE device provided by mobile networks (4G/5G). Especially in economically less developed regions, FWA will increasingly displace traditional fixed network connections as a more cost-effective alternative.

2.1.2 National Status

In Switzerland, the federal government is of the opinion that a powerful telecommunications infrastructure is of high importance for the economy and society [14]. Therefore, a rapid expansion of powerful 5G networks is important. According to the operators Swisscom, Sunrise, and Salt, 7,500 new antenna sites and investments of CHF 3.2 billion are required for this [14]. The three providers together operate almost 20,000 sites [16]. Their market share by number of customers was 54.3 % for Swisscom, 23.6 % for Sunrise, and 17.1 % for Salt at the end of 2023 [17]. The market penetration was 128.9 %. This means that there are more active SIM cards than inhabitants [18].

To protect the population from scientifically proven damage due to non-ionizing radiation (NIS), the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has defined recommended limit values [19]. These were adopted by the federal government in the Ordinance on Protection against Non-Ionizing Radiation (NISV) as immission limit values and correspond to the EU recommendation. These must be complied with at all locations where people can stay. Due to health concerns, so-called system limit values were defined. This stricter limit value is 10 % of the immission limit value and must be complied with at locations with sensitive use (OMEN). These are areas where it is assumed that people stay regularly for longer periods. The electric field strength there is one-tenth of the permissible value in Germany and France. The power of an electromagnetic wave is proportional to the square of the electric field strength. A field strength reduced by a factor of 10 thus leads to a transmission power reduced by a factor of 100 [20].

2.1.3 Cellular Network Generations

Approximately every ten years, a new cellular network generation is introduced [14]. Each of these has a higher data transmission rate, lower latency, and a higher number of devices connected simultaneously. Until the introduction of the sixth generation (6G Vision) around 2030, the fifth generation (5G) is currently being expanded. Also practically relevant is the fourth generation (LTE), which was expanded from 2012. The third generation (UMTS) will be discontinued by Swisscom by the end of 2025 [21]. The second generation (GSM) was discontinued by the three providers between 2021 and 2023 [22]. Newer generations tend to use higher frequency bands, which allow for higher data transmission rates. However, these frequencies are more sensitive to obstacles and have a shorter range. Therefore, more sites are required to achieve the same coverage. [14]

2.1.4 Network Architecture - optional

The network architecture of a cellular network can be divided into various components [6], [10]:

- **Access network:** The access network receives signals from the end device (e.g., smartphone) and forwards them to the core network. It includes the end devices, the transmitting systems, and the radio connection between them.
- **Core network:** The core network processes, controls, and mediates the connections and enables connections to external networks such as the Internet or the fixed network. Each operator has its own core network.
- **Backhaul connection:** The two networks are connected via the backhaul connection, which is preferably implemented as a line-based connection via fiber optic due to its high capacity. However, in remote areas, it can also be implemented as a microwave connection.

The **base station** is the central processing unit for controlling data transmission and is the heart of each system. Each base station also has at least one **antenna** through which bidirectional communication with the end device takes place via electromagnetic waves. Typically, three sector antennas are used per system, each radiating in a sector of 120 degrees. These are arranged in different planes for different technologies. Each antenna sector defines a **radio cell**. This results in an idealized hexagonal basic pattern. [10]

2.1.5 Site Classification

While in radio network planning the classification by cell size (macrocells, microcells, picocells, femtocells) is common [6], the following classification (see 2.2) has established itself in Swiss site planning:

- **Greenfield site:** This type of site is mainly found in rural areas. Characteristic of this is a usually between 20 and 50 meters high, freestanding mast.
- **Rooftop site:** This type of site is mainly found in populated areas. Characteristic of this is the placement on the roof of an existing building. Depending on the chosen mast construction, further distinctions can be made:
  - **Stand-mounted pole [2]:** Mast not firmly connected to the building, which is placed on a steel substructure and placed on the roof.
  - **Wall-mounted pole [3]:** Mast firmly connected to the building, which is mounted on the facade.
  - **Attic-mounted pole [4]:** Mast firmly connected to the building, which is mounted inside the building and protrudes through an opening in the roof to the outside.

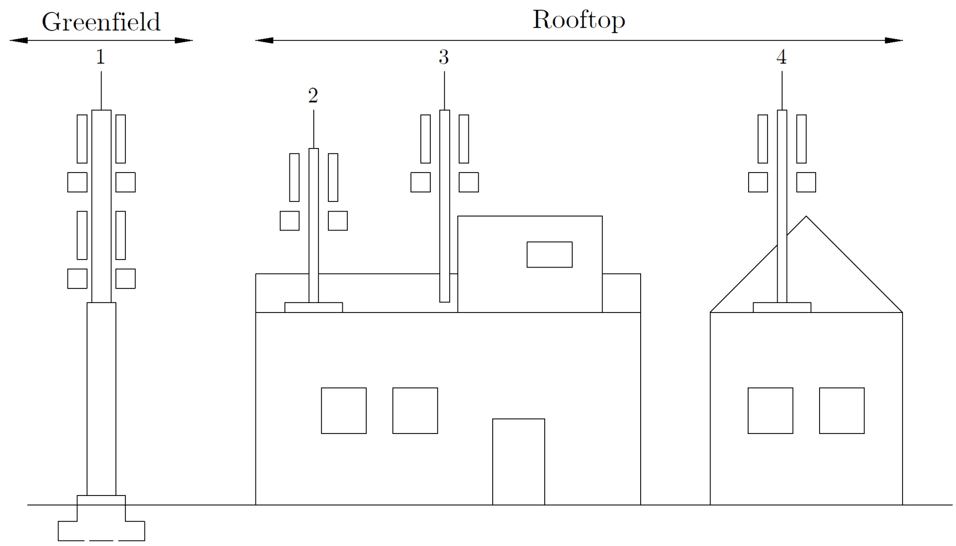


Figure 2.2: Site Classification

2.2 Building Information Modeling (BIM)

Building Information Modeling (BIM) is primarily a methodology for the digital planning, execution, and management of buildings throughout their entire life cycle [23]. The underlying processes have been internationally standardized with ISO 19650. To precisely distinguish it from the tool that enables this methodology, it will be referred to as **BIM software** in the following. In practice, BIM is often used as a synonym for model-based planning, although BIM is actually a broader approach that goes far beyond 3D modeling.

For the literature analysis, the two textbooks [23], [24] were consulted. Due to their comprehensive content, no further scientific publications were consulted. The following section summarizes key findings from the literature analysis.

2.2.1 Characteristics of a BIM Model

A **BIM model** consists, like the three-dimensional **CAD model**, of geometric data in three-dimensional space. However, in addition to the geometric data, the BIM model contains additional information referred to as **attributes**. While the CAD model represents an aggregation of purely geometric primitives (points, lines, surfaces), the BIM model consists of parameterized objects. These are intelligent **components** that can contain attributes such as material and costs in addition to their geometry. This information must be represented graphically or textually in the CAD model. Additionally, components can be semantically linked to model relationships. From a created BIM model, floor plans, sections, and views as well as item lists and quantity calculations can be automatically derived. Changes to the model are automatically reflected in the plans. This is a significant advantage over CAD planning, where all changes must be manually implemented in the plans. [23]

Example Civil Engineering
A ceiling slab of a single-family house is to be lowered by 10 cm.
CAD [1]*: The ceiling must be adjusted in all sections in the formwork and rein-*

[1]Modern CAD systems now also have semi-automated functions.

forcement plans. The rebar list must be updated manually.

***BIM**: In the BIM model, the component `ceiling` is lowered. The change is automatically reflected in the formwork and reinforcement plans. The reinforcement list is automatically updated.*

2.2.2 BIM Terminology

Standardized metrics are available for evaluating and classifying BIM processes and BIM models. These enable an objective evaluation and facilitate communication between project participants. The most important metrics are:

Level of Development (LOD)

The **level of development (LOD)** of a model indicates how much project information is already contained in the model. This consists of the degree of elaboration of the geometry (LOG) and the depth of the alphanumeric information (LOI):

$$\text{LOD} = \text{LOG} + \text{LOI} \tag{2.1}$$

The LOD thus indicates the level of completion of a model at a specific project phase. This is marked with numbers between 100 and 500 (see 2.3). The level of detail increases with increasing number. As the planning progresses, the LOD usually increases. Since a high LOD is associated with a higher workload, it is important to determine how many details are useful at what time. This is indicated by the Level of Information Need (LOIN). [23]

Figure 2.3: Level of Development (LOD) [25]

BIM Dimensions - optional

The **BIM dimension** describes the depth of information of the attributes. It is indicated by a value between 3D and 7D. The level of detail increases with increasing number. [24]

Dimension	Additional Attributes	Use Cases
3D	None	Geometric modeling
4D	Time	Construction scheduling, project phases
5D	Cost	Quantity takeoff, pricing, budgeting
6D	Efficiency & Sustainability	Energy performance, lifecycle assessment
7D	Facility management	Operations, maintenance, asset tracking

Table 2.1: BIM Dimensions and Information Depth

BIM Types - optional

BIM application forms are distinguished in terms of two dimensions: [23]

1. **Depth of Integration:** Quantity measure that describes the extent to which a BIM model is integrated into the value chain. A low depth of integration exists when BIM is only used in a single phase. A high depth of integration means that BIM is used throughout the entire life cycle.

2. **Software Independence:** Quality measure of interoperability, i.e., the ability to use BIM models and data outside of specific software families or providers.

The following four BIM types result from the expression of the two dimensions:

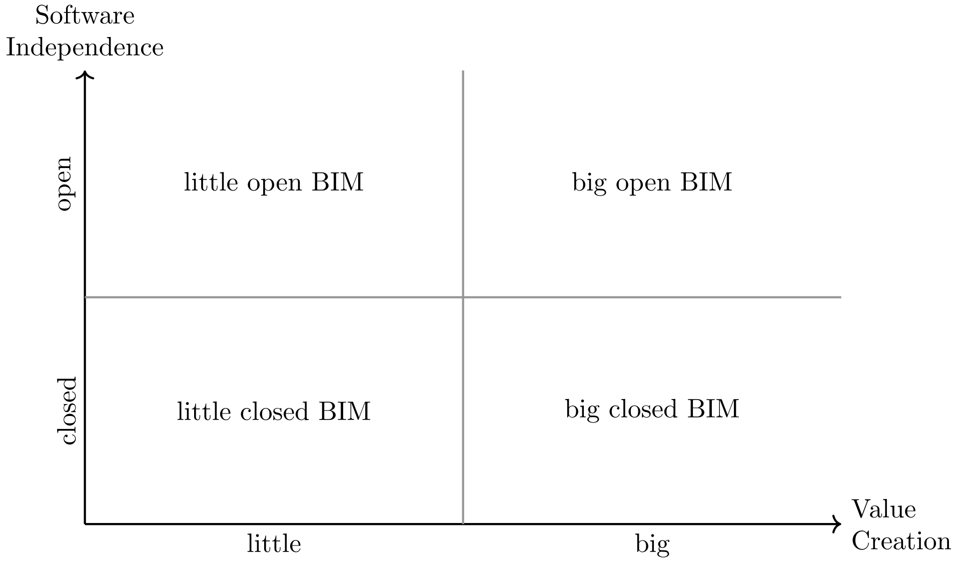


Figure 2.4: BIM Types

BIM Maturity Level - optional

The **BIM maturity level** is a quality measure that describes how systematically and comprehensively BIM is implemented in a company or project. The focus is on data networking, standardization, and collaboration between the participants. According to VDI 2552, the following four maturity levels are distinguished: [2], [23]

2.2.3 BIM Management - optional

BIM management involves the strategic and operational control of BIM. The aim is to standardize workflows and improve collaboration. In this subchapter, three tools will be presented (see 2.5), which will be used in the case study.

Exchange Information Requirements (EIR)

The **Exchange Information Requirements (EIR)** correspond to a specification tailored to BIM. They describe why which information is needed when. They define the client's requirements for BIM processes, data, and collaboration throughout the

Level	BIM Usage	Description
0	None	Traditional 2D CAD drafting is used with no object-based modeling or intelligent data sharing. Collaboration is minimal, and document exchange is paper-based or in simple file formats.
1	None	Combination of 2D and 3D CAD tools. While 3D models may be used internally, there is no standardized collaboration between different disciplines. Data exchange remains file-based without integrated workflows.
2	Collaborative	Different disciplines work on their own BIM models, which are then shared and combined at specific project stages. Collaboration is structured, but data exchange is still semi-automated, requiring manual coordination. Lifecycle phases are considered separately.
3	Integrated	All disciplines collaborate in a fully connected and shared BIM environment. A single, integrated model covers the entire building lifecycle, from design to operation. Automated data exchange and real-time collaboration enable seamless workflows.

Table 2.2: BIM Stages and Their Characteristics

entire project life cycle. This includes specifications for model structure, level of detail, data exchange formats, responsibilities, and collaboration methods. [23]

BIM Execution Plan (BEP)

The **BIM Execution Plan (BEP)** corresponds to a specification tailored to BIM. It describes how the requirements from the **Employer's Information Requirements (EIR)** are implemented by the contractor in the project. [23]

BIM Modeling Guidelines

The **BIM modeling guidelines** define how a BIM model should be structured and organized. For this purpose, standards, methods, and requirements for creation and management are defined. They ensure uniform data structures, better collaboration, and high model quality. Typically, the modeling guidelines are defined or referenced in the BEP. [23]

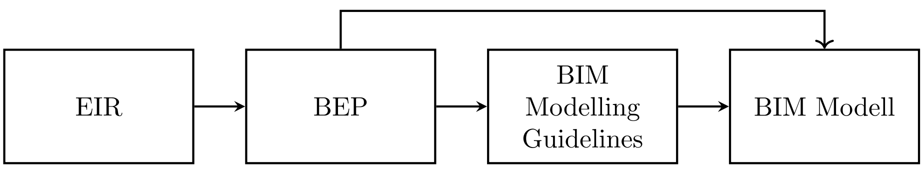


Figure 2.5: Simplified BIM Management Process Flow

2.3 Scan-to-BIM

Renovation projects are becoming increasingly important in the Swiss construction industry. The construction expenditure for new buildings has remained almost the same since 1980. In contrast, investments in renovations, extensions, and demolitions have more than tripled over the same period [26]. As a result, the total Swiss investments in renovations, extensions, and demolitions already account for 66 % of those for new buildings.

At the same time, the documentation of private existing buildings is often incomplete [27], [28]. Especially older buildings often have only incomplete or outdated plan documents. Although building permit plans can often be found in municipal archives, these document the original construction status, are often outdated, and in low detail. In Switzerland, 81.5 % of buildings were constructed before the turn of the millennium [29]. If plan documents exist, they are usually only available in paper form. However, even for newer buildings, editable CAD or BIM files are usually not available. According to Swiss law, the copyright to plans remains with the respective planner. The SIA 102, which is often contractually included, grants the client the right to copies of the work products. However, paper plans or PDF files are sufficient to fulfill this obligation.

As planners are reluctant to provide editable data due to liability risks and clients are usually satisfied with paper or PDF plans, a more comprehensive regulation is often dispensed with. This means that even for newer buildings, no digitally processable planning documents are available, making digital documentation of existing buildings significantly more difficult. For model-based planning, methods are therefore required that can reliably convert the physical construction status into a BIM model. One possibility is to manually reconstruct the model from existing construction plans. However, this approach is time-consuming and error-prone, especially if the plans are incomplete or outdated. A more efficient solution is **Scan-to-BIM**. It is a process in which a physical building is precisely captured using reality capture technologies such as LiDAR or photogrammetry and converted into a BIM model. This enables an exact digital representation of the as-built condition and provides a reliable basis for further planning.

How this process works in detail is examined below based on a literature analysis. Textbooks from scientific publishers that deal with Scan-to-BIM as a central topic could not be identified. To determine the current state of research, the scientific publications [30], [31], [32], [33] were consulted. The workflows described therein each comprise three to six phases (see 2.3). While the work of [30] and [31] consider the entire Scan-to-BIM process from defining information requirements to modeling, the focus of [32] and [33] is on the technical steps to convert point clouds into a BIM model. In addition, the textbook [34] on point cloud processing was consulted. From the analyzed literature, an abstracted Scan-to-BIM workflow with four process steps was derived (see 2.6). The focus is on the technical conversion of the point cloud into a BIM model, which is understood by [30] and [31] as a sub-process of the entire Scan-to-BIM process. This workflow is presented below and forms the basis for the development of an application-oriented framework in the context of the case study in the next chapter.

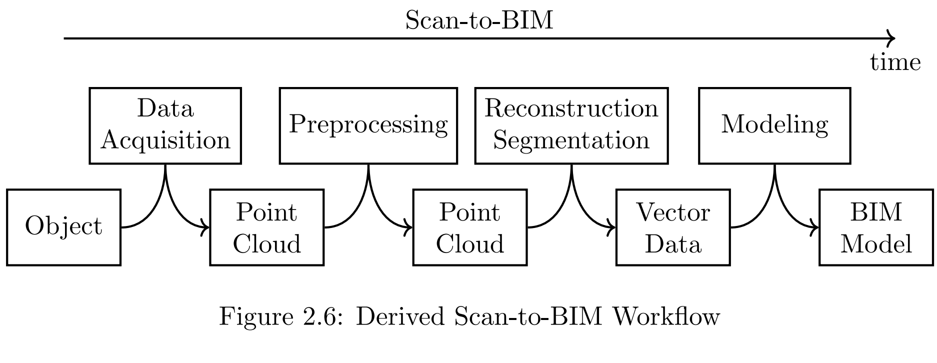


Figure 2.6: Derived Scan-to-BIM Workflow

Paper	Workflow
[30]	1. Identification of information requirements 2. Determination of required scan data quality 3. Scan data acquisition 4. As-is BIM reconstruction
[31]	1. Classification of considered elements 2. Determination of required level of detail 3. Scan data acquisition 4. Point cloud registration and segmentation 5. As-built BIM model generation 6. Analysis
[32]	1. Data acquisition 2. Data preprocessing 3. Modeling
[33]	1. Data capture 2. Semantic segmentation 3. BIM model

Table 2.3: Overview of Scan-to-BIM workflows described in selected studies

2.3.1 Data Acquisition

Data acquisition is done using reality capture. A physical object is digitally captured and represented using sensors. Two main technologies are used for Scan-to-BIM [33]:

- **Light Detection and Ranging (LiDAR):** LiDAR is an active, direct measurement method for distance determination. An emitter sends out laser pulses that are reflected by objects and received by a detector. The distance is calculated from the measured time of flight. A point cloud is directly generated as the native output format. LiDAR scanners can be divided into three categories depending on the chosen platform:

  1. **Terrestrial LiDAR Scanner (TLS):** stationary on a tripod, for precise environment capture.
  2. **Mobile LiDAR Scanner (MLS):** handheld, flexible for tight or hard-to-reach areas.
  3. **Airborne LiDAR Scanner (ALS):** mounted on drones, ideal for facades or larger areas.

- **Photogrammetry:** Photogrammetry is a passive, indirect measurement method based on the evaluation of overlapping photos from different perspectives. Point clouds or meshes can be reconstructed from image geometry and perspective differences.

LiDAR usually has higher accuracy than photogrammetry and is ideal for capturing interiors and poor lighting conditions. Photogrammetry, on the other hand, does not require expensive special hardware and is therefore a relatively cost-effective alternative. It is often used in combination with drones for capturing exterior facades [33]. The following two 3D representations are common output formats [32], [34]:

- **Point Cloud:** A point cloud is a set of points in three-dimensional space. Each point represents a surface position (x, y, z) of the scanned object. In addition to the position, the points can be assigned additional attributes such as color values (r, g, b) or a normal vector (nx, ny, nz). The normal vector describes the orientation of the surface at the respective point position and serves as an input parameter for many algorithms. Point clouds are particularly suitable for precise analyses.

- **Mesh:** A mesh is a planar 3D representation of an object consisting of a set of vertices and their connections (edges and faces). The faces are usually defined as triangles, creating a so-called triangle mesh. Meshes are particularly suitable for realistic visualizations.

The focus of this work is on point clouds. The central quality metrics for this are **wieserKursGeodaetischeMesstechnik2023**:

- **Precision:** Describes the repeatability of the measurement. It indicates how consistent the individual measurements are.
- **Trueness:** Describes how much the mean of many measurements deviates from the true value.
- **Accuracy:** Describes how much a single measurement deviates from the true value. It results from the sum of precision and trueness.
- **Coverage:** Describes how completely the space to be captured is covered. It is a measure of the completeness of the point cloud.
- **Point Density:** Describes how many measurement points were captured in a point cloud per unit area. It is a measure of the detail resolution of the point cloud.
- **Resolution:** Describes the smallest spatial distance that a sensor system can distinguish or capture when scanning. It determines how finely details can be represented in the point cloud.

2.3.2 Preprocessing

In the **Preprocessing** step, the point cloud is prepared for further analysis. The following steps can be performed [33], [34]:

Registration

Since this step is done automatically in the context of bundle block adjustment in photogrammetry, the registration of LiDAR point clouds is considered below. In each scanning process, a point cloud is captured in its own local coordinate system (LCS). To transfer the point clouds to a common coordinate system, the point clouds must be spatially aligned with each other. For this purpose, the local coordinate systems are transformed into a local coordinate system (LCS) using a rigid transformation (translation, rotation). The aim is to create a coherent, complete point cloud in which all subareas are correctly positioned relative to each other. The methods can be divided into two categories:

1. **Coarse Registration:** Coarse registration is the first step in the registration process and serves to roughly align two or more point clouds that are in different coordinate systems. The aim is to create an approximate overlap so that subsequent fine registration is possible. Coarse registration can be done manually or automatically. In automated methods, for example, characteristic features in the point clouds are detected and matched with each other.

2. **Fine Registration:** Fine registration is the second step in the registration process and refines the coarse alignment by calculating a precise transformation between overlapping areas of the point clouds. Fine registration is usually done automatically and is often based on iterative algorithms that minimize the deviation between the point clouds.
Example: Iterative Closest Point (ICP)

Georeferencing

Georeferencing is the process of transferring a point cloud from a local coordinate system (LCS) to a higher-level, global coordinate system (GCS). The aim is to spatially locate the point cloud correctly in relation to real-world coordinates so that it can be combined and reused with other geodata. Georeferencing often uses reference points, so-called Ground Control Points (GCPs). These are distinctive points in the real world whose coordinates are known. The point cloud is then transformed into the GCS using a Helmert transformation (translation, rotation, scaling). The accuracy of the georeferencing depends on the number and geometry of the GCPs. The more GCPs are used, the more accurate the transformation. [35]

Filtering

Point clouds often contain unwanted points that affect the quality of the data. These can be caused by measurement noise, outliers, or unwanted objects. Filtering is used to clean the point cloud of such unwanted points. The following filters can be applied [34]:

1. **Noise Filter:** Noise refers to random, small-scale deviations of the measurement points from their actual position. It can be caused by sensor noise, unfavorable surface properties, or external influences such as lighting conditions. Noise filters are used to improve the quality of the point cloud by reducing these deviations or removing affected points.
Example: Moving Least Squares Filter (MLS)

2. **Outlier Filter:** Outliers are individual measurement points whose position significantly deviates from the surrounding point distribution and do not belong to the actual object geometry. They are often caused by measurement errors, reflections, or disturbances during data acquisition. Outlier filters are used to improve data quality by detecting and removing such points.
Example: Statistical Outlier Removal Filter (SOR)

Downsampling

Downsampling refers to methods for selectively reducing the number of points within a point cloud. The geometrically essential structures should be preserved. The aim is to reduce the amount of data to increase the efficiency of subsequent point cloud processing.
Example: Voxel Grid Downsampling, Farthest Point Sampling (FPS), Normal Space Sampling (NSS)

2.3.3 Geometric Reconstruction

Geometric reconstruction refers to the process of creating a 3D model from the point cloud. Relevant geometric structures of the scanned object are identified and transferred into a suitable 3D representation. Geometric reconstruction can be divided into two main categories [36]:

1. **Rule-based Methods** Rule-based methods extract geometric primitives based on predefined features from a point cloud. They follow clearly defined algorithms. These methods work well with clean, structured point clouds [36].
   Example: RANSAC, PolyFit

2. **Learning-based Methods:** Learning-based methods extract geometric primitives based on self-learned features from a point cloud. They require large annotated training datasets. They are more flexible and can also be used with unstructured point clouds. However, these methods are more computationally intensive and require more processing time [36].
   Example: PointNet++, PointCNN

2.3.4 Semantic Segmentation

Semantic segmentation refers to the process of dividing a point cloud or mesh into semantically meaningful classes. The aim is to recognize the geometric structures of the scanned object and assign them a semantic meaning (e.g., wall, slab, roof). Segmentation can be rule-based or learning-based [37].

2.3.5 Modeling

Modeling refers to the process of creating a structured BIM model from captured data. Both geometric and semantic information are transferred into parameterized components. These components are defined by changeable parameters (e.g., length, height, material), allowing for efficient editing and adaptation of the model. [32]
Two approaches can be distinguished:

1. **Manual Modeling:** In manual modeling, the components are created manually from the point cloud or mesh. This is a time-consuming process. Manual modeling is suitable for complex geometries where automated methods have difficulties.

2. **Automated Modeling:** In automated modeling, algorithms are used to automatically generate the components from the point cloud or mesh. Automated modeling is suitable for structured geometries where clear rules can be defined.

Chapter 3

Methodology

In this chapter, the methodological approach of this work is described. It explains how the Scan-to-BIM framework was developed and which steps were followed in the process.

> Without a framework that is shared by authors, reviewers, and editors, DS research runs the danger of being mistaken for poor-quality empirical research or for practice case study“ [38].

To avoid this, the scientifically grounded Design Science Research Methodology (DSRM) by Peffers et al. [38] is used in this work. This methodology provides a structured framework for systematically developing innovative artifacts while generating scientific insights. The DSRM consists of six steps that can be iteratively traversed if necessary (see Figure 3.1).

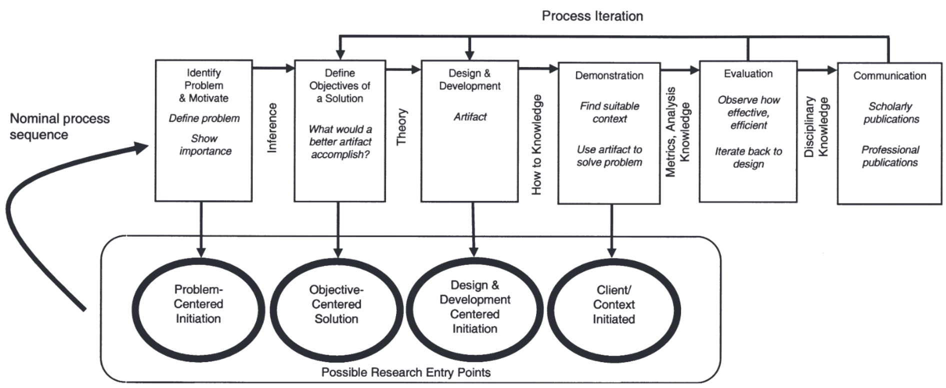


Figure 3.1: Design Science Research Methodology (DSRM) [38]

The implementation of the six steps is carried out within the classic structure of a scientific work. As an artifact, this chapter develops a Scan-to-BIM framework based on the literature analysis. This framework illustrates at a tactical level how an automated Scan-to-BIM workflow could look like. In the next chapter, a Scan-to-BIM pipeline is developed based on the framework. This shows at an operational level that an automated Scan-to-BIM workflow is possible. In the following chapters, the framework is then evaluated.
The following table 3.1 shows the mapping of the DSRM steps to the chapters of this work.

DSRM Step	Thesis Chapter
1. Problem Identification and Motivation	1.2: Research Gap
2. Definition of the Objectives for a Solution	1.3: Research Objectives
3. Design and Development	3.1: Design and Development
4. Demonstration	4: Case Study
5. Evaluation	5: Results
	6: Discussion
6. Communication	7: Conclusion

Table 3.1: Mapping of DSRM steps to thesis chapters

3.1 Design and Development

3.1.1 Data Acquisition

The starting point of the framework is a point cloud that contains information about the entire outer shell of the building to be modeled. If the building is part of a larger point cloud, it must first be isolated.

Due to the high acquisition speed and often better coverage, the use of a drone for data acquisition is recommended. Requirements for the quality metrics of the point cloud were not systematically investigated. However, given the preprocessing steps and the already high level of generalization in geometric reconstruction, it can be assumed that most point clouds captured with current drones will meet the requirements.

Since missing areas cannot be reconstructed, coverage is to be considered the central quality criterion of the point cloud. In addition, trueness is likely to be more relevant than precision, as outliers are removed during preprocessing and point positions are smoothed or averaged. A particularly high point density can be dispensed with, as the number of points in average-sized buildings must be reduced anyway to ensure the convergence of geometric reconstruction.

3.1.2 Preprocessing

For preprocessing the point clouds, the use of an outlier filter and downsampling is recommended.

The effectiveness of an outlier filter was not systematically investigated in this work, but its use generally seems reasonable, as gross errors can affect the trueness of the reconstruction.

Downsampling, on the other hand, is essential, as the runtime of geometric reconstruction increases superlinearly with the number of points. In average-sized buildings, this can lead to runtime overruns or instabilities during geometric reconstruction without reducing point density.

The two preprocessing steps will be described in detail below:

Statistical Outlier Removal (SOR)

Statistical Outlier Removal removes points that are significantly further away from their neighbors than the average. For each point $i = 1, \ldots, n$, a local neighborhood model is calculated with k nearest points, and the distances d_{ij} to the neighbors $j = 1, \ldots, k$ are determined.

The mean distance μ and the standard deviation σ of the point-neighbor distances are given by:

$$\mu = \frac{1}{nk}\sum_{i=1}^{n}\sum_{j=1}^{k} d_{ij}, \quad \sigma = \sqrt{\frac{1}{nk}\sum_{i=1}^{n}\sum_{j=1}^{k}(d_{ij}-\mu)^2}$$

A point is removed if its average neighbor distance lies outside a defined range. For example, a point i is removed as an outlier if:

$$\bar{d}_i > \mu + \alpha \cdot \sigma$$

where $\bar{d}_i$ is the average distance of point i to its k neighbors and α is a freely selectable threshold (typically e.g. $\alpha = 1.0$-2.0). [34]

Voxel Grid Downsampling

Voxel Grid Downsampling reduces the number of points in a point cloud by dividing the space into a regular 3D grid (voxel grid) with a fixed cell size r. Within each voxel cell, a representative point is determined (e.g., randomly, center, or centroid), which replaces the remaining points.

First, the minimum and maximum coordinates are determined:

$$x_{\min} = \min(x_1, \ldots, x_n), \quad x_{\max} = \max(x_1, \ldots, x_n)$$

Similarly for y and z.

Each point $p_i = (x_i, y_i, z_i)$ is then assigned to a voxel cell using the discrete index

$$i_x = \left\lfloor \frac{x_i - x_{\min}}{r} \right\rfloor, \quad i_y = \left\lfloor \frac{y_i - y_{\min}}{r} \right\rfloor, \quad i_z = \left\lfloor \frac{z_i - z_{\min}}{r} \right\rfloor$$

Exactly one point is retained per cell to approximate the point cloud. [34]

3.1.3 Geometric Reconstruction

For geometric reconstruction, the framework *PolyFit* by Nan et al. **nanPolyFitFramework2023** is proposed. It extracts connected planar surface regions from a point cloud and reconstructs them as a triangulated but globally planar mesh. The mesh is manifold (topologically correct) and watertight, meaning it has no holes and no overlapping surfaces. The framework focuses on reconstructing flat surfaces, making it suitable for most applications in construction, as most building components like walls, ceilings, and floors are flat. However, it is not suitable for curved geometries. It should also be noted that the components themselves are not modeled, but rather the envelopes defined by their surfaces.

The framework is implemented in C++ and publicly available on GitHub [39]. Initially, planes in the point cloud are identified using the RANSAC (Random Sample Consensus) algorithm. Similar planes are merged to obtain robust surfaces. Pairwise intersections of the planes create polygonal surfaces. Binary linear optimization selects a subset from a set of candidate surfaces $F = \{f_1, f_2, \ldots, f_N\}$ that best describes the point cloud while forming a compact, topologically correct model.

Objective Function:

$$\min_{\mathbf{x}} \quad \lambda_f \cdot E_f + \lambda_m \cdot E_m + \lambda_c \cdot E_c$$

Explanation:

- $\mathbf{x} = (x_1, \ldots, x_N)$ is a vector of binary decision variables:

$$x_i = \begin{cases} 1, & \text{if surface } f_i \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$$

- E_f: *Data Fit* - prefers surfaces that fit well to the point cloud.
- E_m: *Model Complexity* - penalizes sharp edges and small details.
- E_c: *Point Coverage* - prefers surfaces that cover as many points as possible.
- λ_f, λ_m, λ_c: weighting factors to control the influence of these terms.

Constraints:

$$\sum_{j \in \mathcal{N}(e_i)} x_j \in \{0, 2\} \quad \forall e_i \in E$$

- Each edge e_i must either not be used at all or be used by exactly two surfaces to ensure a *manifold* and *watertight* model.

$$x_i \in \{0, 1\} \quad \forall i = 1, \ldots, N$$

- Binary decision: surface is either included or discarded.

3.1.4 Semantic Segmentation

In order to transfer the mesh from the geometric reconstruction into a BIM model, the surfaces must first be semantically segmented. This means that the surfaces need to be assigned to the corresponding building components. A custom rule-based segmentation method is applied, based on the properties of the surfaces. The segmentation is performed in two steps:

1. **Feature Extraction:** First, the mesh model is oriented so that the largest surface lies in the x-y plane. Then, for each surface of the mesh, the associated normal vector is calculated, which describes the spatial orientation of the surface.

2. **Classification:** The surfaces are then classified based on the orientation of their normal vectors into the following classes:

$$\text{SurfaceType}(n_i) = \begin{cases} \text{Wall}, & \text{if } |\hat{z}_i| \approx 0 \\ \text{Slab}, & \text{if } \sqrt{\hat{x}_i^2 + \hat{y}_i^2} \approx 0 \\ \text{Roof}, & \text{otherwise} \end{cases}$$

   where n_i is the normal vector of surface i and $\hat{x}_i$, $\hat{y}_i$, $\hat{z}_i$ are the normalized components of the vector. Horizontal surfaces are classified as slabs, vertical surfaces as walls, and inclined surfaces as roofs.

3.1.5 Modeling

In the final step, the semantically segmented mesh is converted into a BIM model. The following approach is recommended:

1. **Automated Modeling:** For each surface of the mesh, a corresponding building component is automatically created in the BIM model. The geometry and relevant properties are extracted from the mesh and transferred to the BIM model. The assignment to a building component type (e.g., wall) is based on the previously defined classes from the segmentation.

   For software-independent implementation, it is recommended to use the IFC interface. This allows for standardized transfer of geometry and building component properties and ensures interoperability between different BIM systems.

   If the downstream BIM software does not fully support IFC, the API of the respective software can be used to programmatically create the components. In cases where IFC support is limited, conversion to a native format of the target software is recommended. This process can be automated using visual scripting environments for parametric design, which are integrated into many BIM platforms.

   Each building component type (e.g., wall) can be assigned a specific building component type (e.g., concrete 25 cm). Native modeling allows for better integration into the respective software environment and facilitates subsequent editing, analysis, and reuse of the generated components.

   At the end of this step, a complete BIM model in LoD 200 should be available.

2. **Manual Modeling:** Depending on the application case, a higher level of detail may be required. In this case, it is recommended to use the automatically generated model as a starting point and then make manual adjustments. This includes adding windows, doors, or other architectural elements that could not be automatically reconstructed from the point cloud. The assignment or adjustment of building component types and properties can also take place in this step to meet project-specific requirements.

   From this extended model, plans and visualizations can then be derived for use in further planning and execution of the construction project.

Chapter 4

Case Study

To demonstrate and evaluate the effectiveness of the developed framework under real-world conditions, a case study was conducted. A pipeline was developed based on the previously established framework.

The case study was carried out in collaboration with Axians, an internationally operating ICT company. The goal was to extract a residential building from a given point cloud, model it as automated as possible, and subsequently derive the plans required for a building application.

4.1 Data Acquisition

The data acquisition was carried out by Axians. Therefore, the design of the acquisition was not part of the case study. The aerial images were captured using a DJI Mavic 3 Enterprise drone. The photogrammetrically generated point cloud covered an area of approximately 700 x 500 m and contained around 33.1 million points.

Specification	**Value**
Camera Model	DJI M3E (integrated)
Sensor Size	4/3" CMOS
Effective Resolution	20 MP (5280 x 3956 pixels)
RTK Support	Yes (integrated RTK module)

Table 4.1: Key camera specifications of the DJI Mavic 3 Enterprise (M3E) [40]

4.2 Preprocessing

First, the target building was isolated using the open-source tool *CloudCompare*. The segmentation was performed manually by drawing a box around the building in the top view with approximately 1 m distance. This reduced the point count to about 780,000 points.

Next, the point cloud was cleaned using a Statistical Outlier Removal (SOR) filter implemented in Python. Points were removed if their average distance to the 20 nearest neighbors was greater than the global mean of these distances plus two standard deviations. This removed approximately 35,000 points, resulting in a reduction of about 4.5%. The remaining point cloud contained around 745,000 points.

Subsequently, the point cloud was further reduced using voxel grid downsampling. It was observed that the mesh generated by geometric reconstruction depends on the number of points and thus indirectly on the chosen voxel size. The voxel size can therefore be considered an additional parameter for controlling the geometric reconstruction, alongside the three PolyFit-internal lambda weights. Since it proved to be the most influential factor in the case study, only the voxel size was considered as a hyperparameter.

4.3 Geometric Reconstruction

The geometric reconstruction was performed using the PolyFit framework in Python. The source code, written in C++, is available on GitHub [39]. To utilize the functions in Python, a corresponding Python binding was created using CMake. Additionally, the Python library *Easy3D*, also developed at TU Delft, was required for the first step of the PolyFit workflow - surface extraction using RANSAC [41].

Since the bindings need to be manually compiled for the target platform (operating system and Python version), the setup process is relatively complex. Therefore, the developed script cannot be easily adopted by other users, which currently limits the productive use of the pipeline.

No invariant parameters were found for the geometric reconstruction that reliably produce good mesh models for different buildings. Therefore, a brute-force approach was chosen, where the voxel size was iterated to generate a variety of mesh models. The model with the subjective best quality was then selected. This model was created from a point cloud with approximately 87,000 points, which corresponds to about one-tenth of the original point cloud. For point counts above approximately 150,000 points, the optimization problem became too complex and led to program termination. The open-source solver SCIP was used for the calculations. The commercial Gurobi solver is available free of charge for scientific projects and is expected to offer better performance [39], potentially allowing for a higher point count. However, since the model quality already reached its maximum at around 87,000 points, the Gurobi solver was not tested.

4.4 Semantic Segmentation

The semantic segmentation was performed using the framework described in Chapter **??**, which was implemented in Python. The surfaces were identified, segmented, and each exported as .obj files. The associated classification was encoded in the filename to avoid the use of additional auxiliary files.

4.5 Modeling

The first part of the automated modeling, the creation of the IFC model, was done in Python. The library *ifcopenshell* was used, which provides an interface for the IFC data structure [42]. The .obj files of the segmented surfaces were read in and integrated into the IFC model. The IFC model was then exported as an .ifc file, creating a base model that can be further processed in various BIM software solutions.

The second part of the automated modeling, the parameterization of the IFC components, was done in the BIM software *Revit* by *Autodesk*. The IFC model was imported and manually parameterized using Revit functions. This workflow was then automated with *Dynamo*, a visual programming environment that has been integrated into *Revit* since 2020 [43].

At this point, the created model was expected to have a Level of Detail (LoD) of 200. Since it was unclear whether the model already met the requirements for building application plans, the Building Permit Office of the City of Zurich was contacted for a general assessment.

> When approving mobile radio installations, different design requirements must be observed depending on location and zone. Therefore, a pure volume model is not sufficient. All structuring elements must also be represented in the elevations. [44]

The response from the building authority indicated that the model in its current form did not meet the requirements for building application plans. It was therefore decided to raise the model to LoD 300.

The refinement of the model was then carried out manually in *Revit*. Windows and balcony railings were integrated into the model. The inserted components were only for illustrative purposes and were not positioned precisely. To keep the effort minimal, pre-installed Revit families were used for the windows. The balcony railings were modeled as simple walls. Additionally, improvements were limited to the two views presented in the building application plans. The roof area was also improved by modeling the missing roof structure, which is relevant for both building application plans and technical facility planning. For representing antenna masts, a Revit family already provided by Axians was used.

Finally, the building application plans were generated from the model using a predefined plan layout. No adjustments were made, as the plans were only for illustrative purposes. A visualization of the model was also created. An environmental model was generated in *Infraworks*, which could be imported into *Revit* via *Navisworks*.

Chapter 5

Results

This chapter presents the results of the case study. It shows what has been created through the application of the framework. The primary result is the BIM model derived from a point cloud. Secondary results include the permit drawing and an animation derived from the BIM model.

5.1 BIM-Model

The IFC model of the five-story residential building, with approximate dimensions of $28 \times 17 \times 16$ m (length $\times$ width $\times$ height), consists of a total of 14 components. Among these are nine walls (`IfcWall`), four slabs (`IfcSlab`), and one roof (`IfcRoof`).

The components are modeled as two-dimensional surfaces in three-dimensional space. The ground slab lies in the XY-plane at height 0. Millimeters were used as the length unit. The components are not parametrically modeled; their geometry cannot be directly modified in the model.

The generated geometry is *manifold* and *watertight*, meaning it is topologically consistent and closed. The model corresponds to a Level of Detail (LOD) of 200.

For the manually improved BIM model, 8 balcony railings, 24 windows, 1 door, 1 roof structure, and 2 antenna masts including RAN equipment were added. One of the predefined window families could be integrated into the IFC walls, so parameterization was omitted. Since the roof slab is not perfectly horizontal, the pavement slabs were adjusted to the slab's course in discrete height steps. The surrounding model represents the approximate terrain and strongly generalized buildings in the vicinity.

5.2 Permit Drawing

The permit drawing was derived from the BIM model and corresponds to the current industry practice in Switzerland. An A3 layout was chosen, consisting of a plan view and two elevations at a scale of 1:200. Additionally, two rendered visualizations were included.

The building dimensions were dimensioned. The mast center was measured from the building edge. Sector designation for the main beam directions was omitted. The plan header comes from an Autodesk template, and the plan header data was not modified.

5.3 Animation

The animation shows a camera tour around the modeled building. Due to technical limitations, the surrounding model could not be rendered. The textures used are simple but allow for a basic spatial representation of the overall scene.

Chapter 6

Discussion

6.1 Evaluation

A comprehensive evaluation of the case study was excluded from the beginning due to time constraints. A ground-truth validation of the model did not take place. Therefore, the evaluation was limited to the following three aspects:

6.1.1 PolyFit Runtime Analysis

To analyze the behavior of the PolyFit algorithm, a runtime analysis was conducted during the development phase. This was performed on an Intel Core i7-9700K 3.60 GHz processor with 32 GB RAM. The runtime was measured for various point cloud sizes.

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6.1.2 Model Quality

To assess the model quality, a purely qualitative analysis was conducted. Both the geometric and semantic quality were evaluated.

Geometric Quality

The geometric quality was assessed based on the visual consistency of the components. The characteristic shape of the building was well represented in the model. No conclusive statement could be made regarding geometric accuracy. The Building Permit Office did not specify concrete accuracy requirements. In practice, a guideline accuracy tolerance of 10 cm is aimed for. It is doubted whether this tolerance was met. A high variation of the generated models was observed, and reproducibility was low. Even with consistent parameters, different models were sometimes generated. It is suspected that the low precision may be due to the non-deterministic RANSAC algorithm or an ambiguity in the optimization problem. Ultimately, the low precision leads to low geometric accuracy.

In addition to geometric accuracy, the completeness of the model is also important. It was observed that some components considered relevant were not included in the model, such as the shaft head.

Another challenge was geometric imperfections. It is assumed that the slabs are slightly less parallel to each other than in the actual building. Additionally, the walls show an unsystematic inclination. While these imperfections may be negligible for permit purposes, they can limit the usability of parameterized components. This seems plausible since, for example, an inclined wall cannot be represented solely by a base line and a corresponding height. Without usability, the component cannot be geometrically adjusted, which can significantly restrict its practical use.

Semantic Quality

The semantic quality of the model was assessed based on the correct classification of the components. Correct classification of components is particularly important for automated parameterization. The 14 components were correctly classified, with the exception of one inaccurately reconstructed wall. The wall was modeled at an angle, resulting in a normal vector with a z-component, which led to its classification as a roof (`IfcRoof`). Thus, the semantic quality is strongly dependent on the geometric quality.

6.1.3 Transferability to other buildings

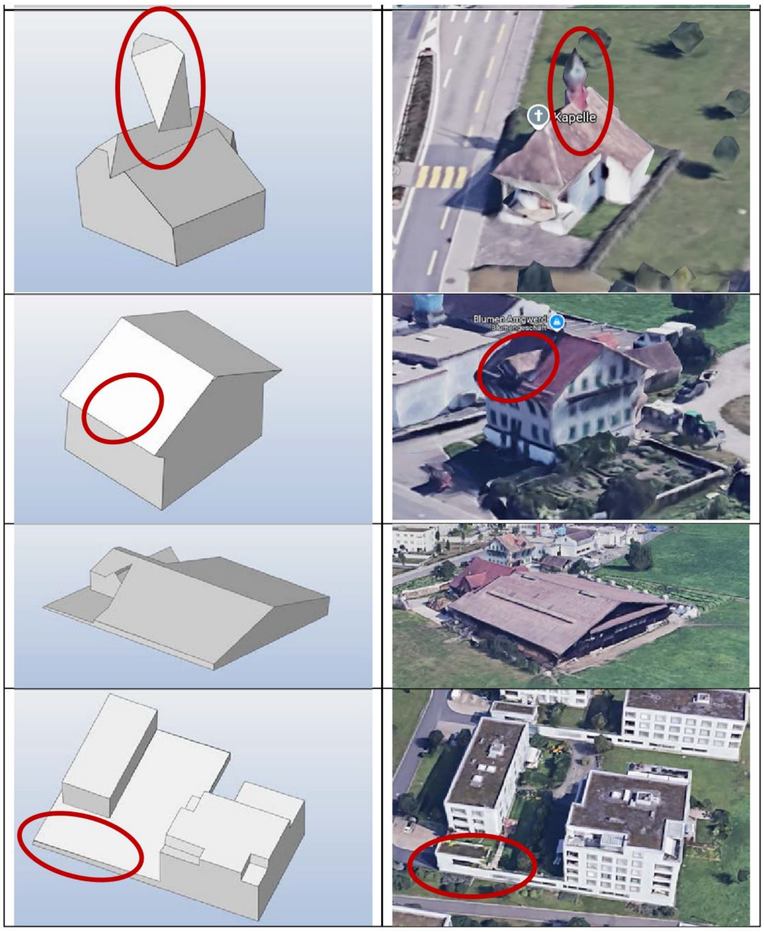

Figure 6.1: Transferability to other building types

To test the transferability of the developed framework to different building types, four buildings were reconstructed as examples, and the results were qualitatively evaluated. The buildings modeled include a chapel (1), a single-family house with a gable roof (2), an agricultural hall building (3), and a modern residential complex (4). The results are shown in Figure 6.1.

1. The weakest result was achieved with building 1. The reconstruction of the round tower top led to geometric artifacts. The characteristic shape of the building could only be inadequately represented in the model.

2. Buildings 2 to 4 were generally reconstructed well, although in models 2 and 4, significant components were lost due to generalization.

Overall, it was shown that the framework is fundamentally applicable to different building types. The results suggest that large-area buildings with simple geometries can be reconstructed more reliably.

6.2 Limitations

The developed framework still has some limitations that may restrict its applicability in practice. The limitations can be categorized based on their origin.

Limitations in Geometric Reconstruction

The biggest limitation is currently related to geometric reconstruction. At the same time, it is the most complex part of the framework, contributed by scientific research, and is unlikely to be optimized further. Limitations associated with this are:

- The framework can only be applied to isolated, individual buildings.
- The framework cannot be reliably applied to curved or complex geometries. What constitutes a complex geometry could not be conclusively defined and must be assessed on a case-by-case basis.
- The framework likely does not meet the accuracy requirements of 10 cm demanded in practice.
- The framework has low reproducibility. The variation of generated models is high. Subjective decisions must be made, further limiting reproducibility.
- The framework leads to geometrically imperfect models. These imperfections can complicate modeling and restrict parameterization.

Limitations in Automation

The automation of the framework is currently incomplete. Manual adjustments must be made to obtain a usable BIM model. These limitations are:

- The framework could not be fully automated. Manual adjustments are necessary to obtain a usable BIM model.
- The framework can currently only generate automated IFC models. The generation of parameterized models is not possible at this time.

Limitations in Usability and Integration

The framework was developed for the case study and not for productive use, leading to further limitations:

- The framework cannot currently be deployed efficiently. Dependencies lead to increased setup effort. Installation requires basic knowledge of Python tooling.

- The framework is not intuitively usable. It consists of several Python scripts, where hyperparameters must still be adjusted in case of poor performance. A technical documentation is missing.
- The framework requires knowledge of manual BIM modeling. Without corresponding knowledge, only an IFC model can be generated with the framework.
- The framework can currently only be applied to .ply point cloud formats. Other point cloud formats are not supported.

6.3 Future Work

The limitations of the framework significantly restrict its applicability in practice. To optimize the framework for productive use, the following points should be addressed:

Future Work in Geometric Reconstruction

The contribution of limitations from geometric reconstruction is overall considered the highest and should therefore be prioritized. At the same time, it is the most complex part of the framework, stemming from research. The likelihood of optimizing the actual algorithm is deemed unrealistic. It is therefore recommended to try alternative tools for geometric reconstruction. Thanks to the modular structure of the framework, tools can be replaced without affecting other parts. Methods based on assumptions like the "Manhattan Assumption" can be promising here. This assumption leads to the geometry of the building being limited to right-angled components, which is likely applicable to many buildings and should result in clean models. For future implementations, the following is recommended:

- **High Priority:** Replace PolyFit with an alternative tool. [45] looks promising based on initial analysis, but accessibility of the source code needs to be verified.
- **High Priority:** Alternatively, it is recommended to contact the developer of PolyFit, Professor Dr. Liangliang Nan from TU Delft. He has been helpful during implementation and could provide valuable insights into potential alternatives.

Future Work in Automation

The automation of the framework is currently incomplete. It is recommended to further advance the automation. The automatic parameterization of the IFC model with Dynamo is considered feasible with little effort. A complete automation beyond that would likely only be achievable with the use of learning-based methods, which would probably require a fundamental redesign of the framework. For future implementations, the following is recommended:

- **Medium Priority:** Automation of the parameterization of the IFC model with Dynamo.
- **Low Priority:** Exploration of learning-based approaches with neural networks, which could be part of a master's thesis.

Future Work in Usability and Integration

If the challenges of geometric reconstruction can be addressed, productive use can be considered. The usability and integration of the framework are currently insufficient and need to be improved. One possible approach is to integrate it into a web service that accepts the point cloud and generates an IFC model from it. This would allow global access to the framework without installation. A graphical user interface (GUI) could visualize the models and assist in finding optimal hyperparameters. For future implementations, the following is recommended:

- **Medium Priority:** Integration of the framework into a web service that accepts the point cloud and generates the IFC model.

Chapter 7

Conclusion

In this thesis, a process was developed that enables the generation of a BIM model from a point cloud. Based on the Design Science Research Methodology (DSRM), a corresponding framework was designed, implemented as a pipeline, and demonstrated in a case study in collaboration with Axians. The case study exemplified that the framework is fundamentally capable of producing a BIM model. This not only answered whether automation is possible but also how it can be concretely realized.

A five-step process was proposed, consisting of *Data Acquisition (1)*, *Preprocessing (2)*, *Geometric Segmentation (3)*, *Semantic Segmentation (4)*, and *Modeling (5)*. With the exception of data acquisition and parts of modeling, the steps were successfully automated. Tools such as *CloudCompare*, *Python*, *Revit*, and *Dynamo* were employed.

Throughout the work, several challenges were identified that currently limit practical applicability. These can be categorized into three areas: *Geometric Reconstruction (1)*, *Automation (2)*, and *Usability and Integration (3)*. Targeted solutions were formulated for each category. If geometric reconstruction continues to improve, the productive use of the framework in site planning for telecommunications equipment appears realistic. This would contribute to increased efficiency in the construction industry.

Data Availability Statement

The source code of this thesis will be published on GitHub at the end of July 2025. A technical documentation will not be provided. The point cloud used as the basis for the case study was provided by Axians and will therefore not be publicly accessible. Questions can be sent via email to leisij@student.ethz.ch.

Conflicts of Interest

The collaboration with Axians was part of a supervised practical project. There was no financial compensation or contractual influence on the content or results of this work.

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