Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Institut für
Bau- und Infrastruktur-
management

Bachelor Thesis

Automating Scan-to-BIM for Telecom Site Planning

A Comparative Analysis and Case Study

Autumn Term 2025

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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

Symbols

Symbols

ϕ, θ, ψ	roll, pitch and yaw angle
b	gyroscope bias
Ω_m	3-axis gyroscope measurement

Indices

x	x axis
y	y axis

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.

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 this context, BIM refers to both the technology (software) and the methodology (processes). 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.

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. [2]. 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. [3].

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-GIS:** Scan-to-GIS involves creating a surface model for use in Geographic Information Systems (GIS). This model often consists of thousands of small triangles (meshes) that are not logically structured geometrically. It lacks semantic information such as object classes or building component properties and is primarily used for visualization and geospatial analysis. While the generation process is relatively quick, subsequent editing or structuring is time-consuming.

  Analogy: Scanning a text document is quick, but editing the text afterwards is difficult.

- **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: Retyping a text document in a word processing program takes longer, but efficient work can be done afterwards.

1.2 Research Objectives and Questions

Both BIM and Scan-to-BIM have been intensively researched in recent years **rochaSurveyScantoBIMPractices2021**.
The existing literature on BIM is extensive, with numerous textbooks and scientific publications available. However, no books from scientific publishers could be identified specifically for Scan-to-BIM. The topic has only been superficially covered in BIM textbooks, with the literature primarily consisting of scientific publications. Common applications are found in the traditional construction sector and the documentation of historical buildings. No publications specifically addressing site planning in the telecommunications industry could be found. The requirements for the generated models vary depending on the application. In the traditional construction sector and historical buildings, both interior and exterior structures are often modeled. In site planning, modeling is mainly limited to exterior structures, resembling Scan-to-GIS procedures. The focus is on automated procedures.

To clarify the research objective, central workflow terms are introduced. These terms are understood as follows in this work:

- **Workflow:** A workflow is a sequence of work steps performed to achieve a goal. At the strategic level, it clarifies technology-independent *WHAT*, *WHEN*, and *WHY* is done.
  Example: Segmentation

- **Framework:** A framework is the sequence of methods that concretize the work steps. At the tactical level, it clarifies technology-independent *HOW* the work steps are performed. Methods can include algorithms or procedures.
  Example: Segmentation by polyfit algorithm

- **Toolchain:** The toolchain is the sequence of tools used to implement the methods. At the operational level, it clarifies technology-dependent *WITH*

WHAT the work steps are performed. Tools can include software, scripts, or platforms.
Example: Segmentation by polyfit algorithm implemented in Python

In a first step, a framework tailored to site planning will be developed using the "Research by Design" methodology. Existing workflows and methods from research will be used for this purpose. In a second step, an operationally executable toolchain will be developed for the framework and implemented.

- **Main Question:** How can the Scan-to-BIM workflow for site planning in the telecommunications industry be automated?
  - **Sub-Question 1:** Which methods are suitable for developing an automated Scan-to-BIM framework for site planning?
  - **Sub-Question 2:** Which tools are suitable for developing an automated Scan-to-BIM toolchain for site planning?

1.3 Thesis Structure

To address the research questions, this thesis is divided into two parts, with each part focusing on one of the research questions:

- **Part 1:** The first part aims to answer the first research question through a comparative analysis. Chapter 2 provides an introduction to the three main topics of telecom, BIM, and Scan-to-BIM, laying the foundation for the subsequent analysis. Chapter 3 delves into the analysis itself, examining several Scan-to-BIM technologies introduced in Chapter 2 and evaluating their suitability. Based on this analysis, a concrete framework is developed.
- **Part 2:** The second part involves applying the developed framework to a practical case study. Chapter 4 identifies the initial problem, while Chapter 5 discusses the results of the implementation. Finally, Chapter 6 summarizes the findings and provides an outlook on future research.

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, ...). [4]. **Cellular communications** is a subfield of this, in which **cellular networks** are used [5]. 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. [6], [7].
- **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 [8].

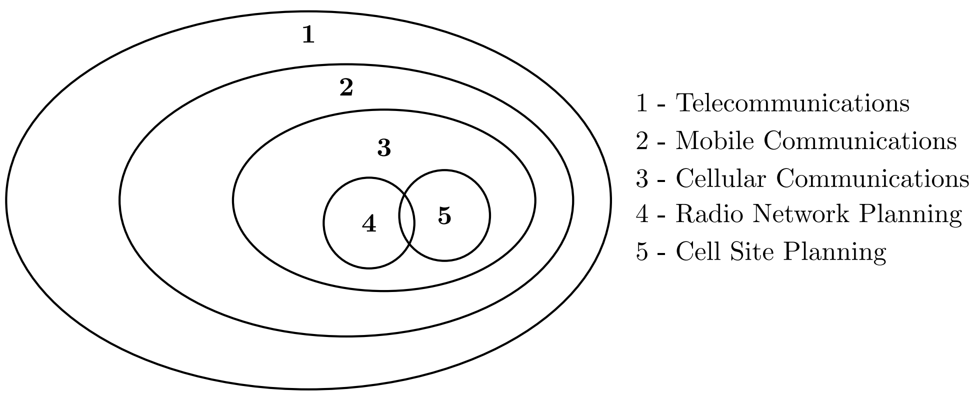

Figure 2.1: Telecommunications Hierarchy

This work focuses on cell site planning. For the literature analysis, two general works on mobile communications from Springer [5], [9] as well as three papers listed under cell site planning [10], [11], [12] 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 [13].

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 [14]. 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 [14]. 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 [13]. 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 [13]. The three providers together operate almost 20,000 sites [15]. 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 [16]. The market penetration was 128.9 %. This means that there are more active SIM cards than inhabitants [17].

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 [18]. 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 [19].

2.1.3 Cellular Network Generations

Approximately every ten years, a new cellular network generation is introduced [13]. 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 [20]. The second generation (GSM) was discontinued by the three providers between 2021 and 2023 [21].

2.1.4 Network Architecture

The network architecture of a cellular network can be divided into various components [5], [9]:

- **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. [9]

2.1.5 Site Classification

While in radio network planning the classification by cell size (macrocells, microcells, picocells, femtocells) is common [5], 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.

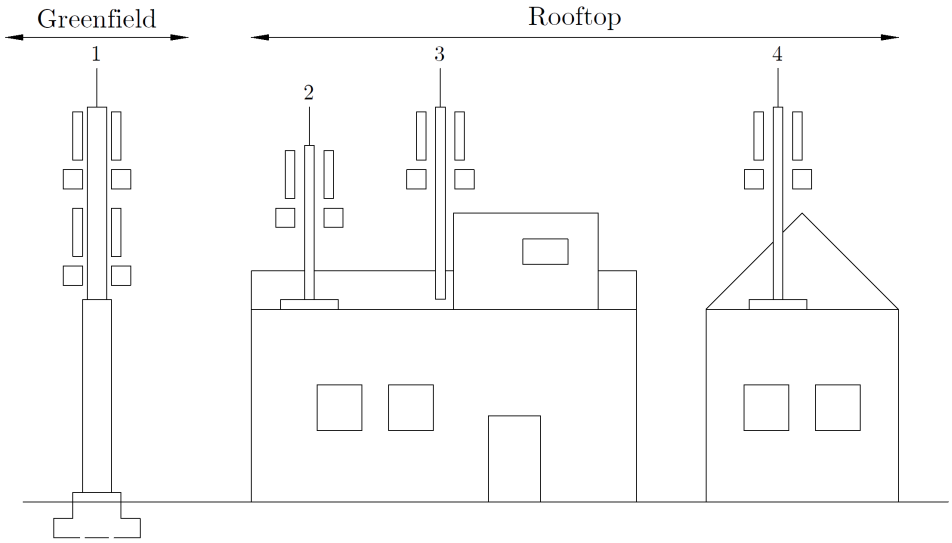

Figure 2.2: Site Classification

2.2 Building Information Modeling (BIM)

Building Information Modeling (BIM) is primarily a methodology for digitally planning, executing, and managing buildings over the entire life cycle [22]. In practice, BIM is therefore often used as a synonym for model-based planning, although BIM can go beyond mere 3D modeling (e.g., 4D). To clearly distinguish it from the tool that enables this methodology, it will be referred to as **BIM software** below.

For the literature analysis, the two textbooks [22], [23] were consulted. Due to their comprehensive content, further scientific publications were not consulted. The following section summarizes key findings of the literature analysis.

2.2.1 Characteristics of a BIM Model

A **BIM model** initially consists, like the three-dimensional **CAD model**, of geometric data in three-dimensional space. In addition to the geometric data, however, 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 parametrized 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. In addition, components can be semantically linked to model relationships. This will be illustrated by the following example. [22]

Example Civil Engineering
A ceiling slab of a single-family house is to be lowered by 10 cm.

***BIM**: The component `ceiling slab` is lowered in the BIM model. The change is automatically reflected in the formwork and reinforcement plans. The reinforcement list is updated automatically. The financial implications can be determined directly via a cost calculation.*

***CAD** [1]: The ceiling slab is lowered in the CAD model. The change is manually transferred to the formwork and reinforcement plans. The reinforcement list must be updated manually. The financial implications must be calculated separately.*

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

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:

BIM Maturity Level

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: [22], [24]

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 2.1: BIM Stages and Their Characteristics

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):

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

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). [22]

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

BIM Dimensions

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. [23]

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 2.2: BIM Dimensions and Information Depth

BIM Types

BIM application forms are distinguished in terms of two dimensions: [22]

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:

2.2.3 BIM Management

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 entire project life cycle. This includes specifications for model structure, level of detail, data exchange formats, responsibilities, and collaboration methods. [22]

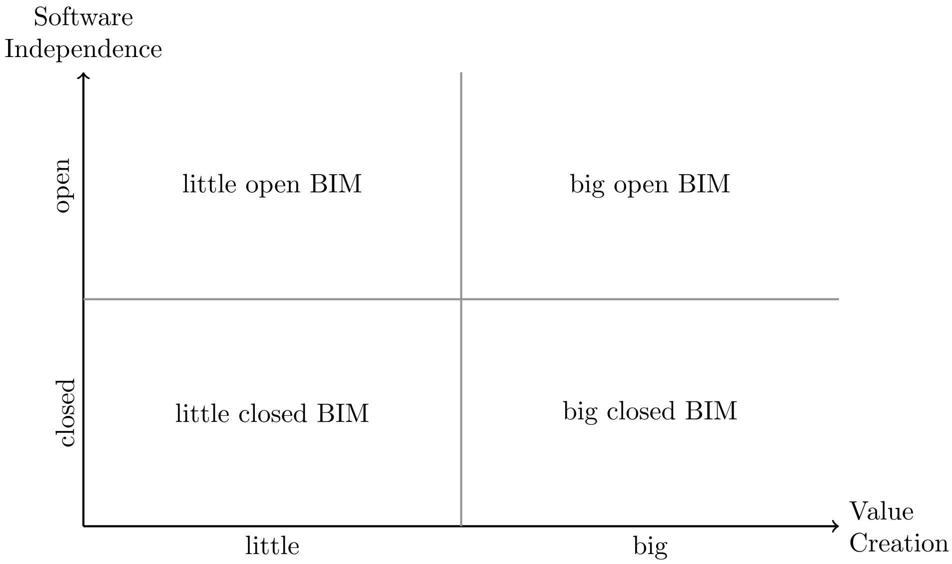

Figure 2.4: BIM Types

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. [22]

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. [22]

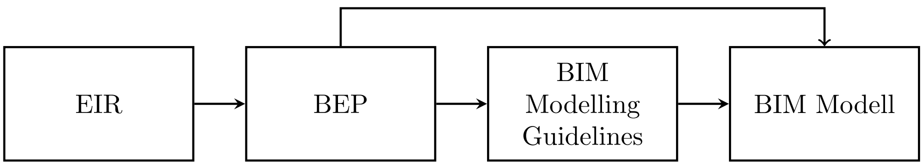

Figure 2.5: Simplified BIM Management Process Flow

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 **dewolfCircularBuiltEnvironmentg**, [27]. 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 [28]. 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 [29], [30], [31], [32] were consulted. The workflows described therein each comprise three to six phases (see 2.3). While the work of [29] and [30] consider the entire Scan-to-BIM process from defining information requirements to modeling, the focus of [31] and [32] is on the technical steps to convert point clouds into a BIM model. In addition, the textbook [33] 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 [29] and [30] 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.

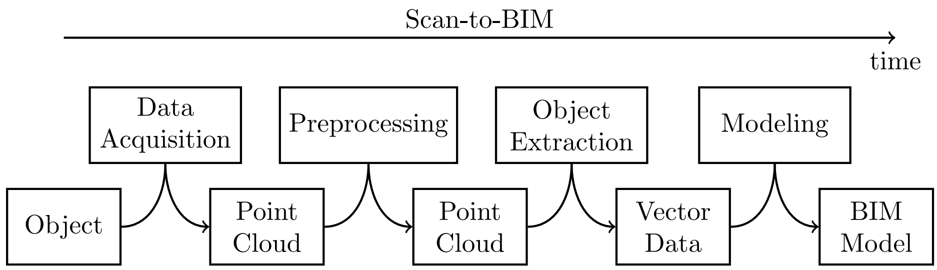

Figure 2.6: Derived Scan-to-BIM Workflow

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 [32]:

Paper	Workflow
[29]	1. Identification of information requirements
	2. Determination of required scan data quality
	3. Scan data acquisition
	4. As-is BIM reconstruction
[30]	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
[31]	1. Data acquisition
	2. Data preprocessing
	3. Modeling
[32]	1. Data capture
	2. Semantic segmentation
	3. BIM model

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

- **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 [32]. The following two 3D representations are common output formats [31], [33]:

- **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 [32]:

- **Accuracy:** Describes how accurately the captured point positions (x, y, z) reflect the actual geometry of the real object. It indicates how large the deviation between the measured value and the true position is.

- **Precision:** Describes the repeatability of the measurement. It describes how consistently the individual point positions are captured when the same object is measured multiple times under the same conditions.

- **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 fine 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 [32], [33]:

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. [34]

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 [33]:

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 Segmentation

Segmentation is a process in which the point cloud is divided into individual objects or components. The following methods are distinguished:

- **Manual Segmentation:** TODO: Description

- **Semi-automatic Segmentation:** TODO: Description

- **Automatic Segmentation:** TODO: Description

2.3.4 Modeling

The **Modeling** step is used to transfer the vector data from the point cloud into a BIM model. The following methods are distinguished:

- **Manual Modeling:** TODO: Description
- **Semi-automatic Modeling:** TODO: Description
- **Automatic Modeling:** TODO: Description

Chapter 3

Methodology

According to Creswell [35], four paradigms are proposed to generate new scientific knowledge: postpositivism, constructivism, transformative paradigm, and pragmatism. Pragmatism is an epistemological paradigm. Truth is evaluated as what works in practice. Research is thus understood as a goal-oriented means to solve concrete problems.

A research approach within pragmatism is Design Science Research (DSR) [36]. It originates from engineering and information sciences and is applied in this work. Innovative artifacts are developed to solve real problems. At the same time, the research should be scientifically founded and generate new knowledge that is generalizable beyond the individual case. DSR thus combines practical utility with theoretical knowledge gain.

To apply Design Science Research as a methodology, various methodological approaches are available. The most widespread [36] is the Design Science Research Methodology (DSRM) by Peffers et al [37]. "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" [37]. To avoid this, six steps are proposed (see fig. 3.1). The individual steps are taken up and implemented in the following chapters (see tab. 3.1).

DSRM Step	**Thesis Chapter**
1. Problem Identification and Motivation	1.1, 3.1
2. Definition of the Objectives for a Solution	1.2, 3.2
3. Design and Development	3.3
4. Demonstration	4
5. Evaluation	5, 6
6. Communication	7

Table 3.1: Mapping of DSRM steps to thesis chapters

The DSRM was chosen because it is particularly well suited for the systematic development and evaluation of technical artifacts. It enables a structured approach to create an automated Scan-to-BIM framework that addresses a real, practice-relevant problem. At the same time, it ensures a scientifically founded derivation and evaluation of the developed solution.

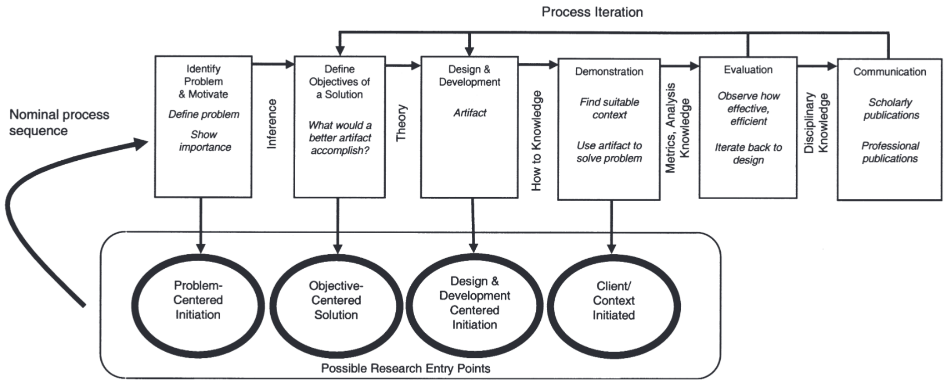

Figure 3.1: Design Science Research Methodology (DSRM) [37]

3.1 Problem Identification and Motivation

The general problem of the industry has already been addressed in the introduction (see 1). Now, the bridge to the concrete problem that is addressed in this work should be built. The work was created in collaboration with Axians Switzerland, a corporate group with around 940 employees [38]. Axians is the ICT brand of VINCI Energies, a business unit of the French group VINCI. With around 285,000 employees [39], VINCI is one of the largest companies in the field of construction, infrastructure, and concessions worldwide.

3.2 Definition of the Objectives for a Solution

3.3 Design and Development

Chapter 4

Case Study

4.1 Introduction

TODO: Provide a brief introduction to the chapter.

4.2 Initial Situation

4.3 Chosen Approach

Chapter 5

Results

5.1 Introduction

TODO: Provide a brief introduction to the chapter.

Chapter 6

Discussion

6.1 Introduction

TODO: Provide a brief introduction to the chapter.

Chapter 7

Conclusion

7.1 Introduction

TODO: Provide a brief introduction to the chapter.

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