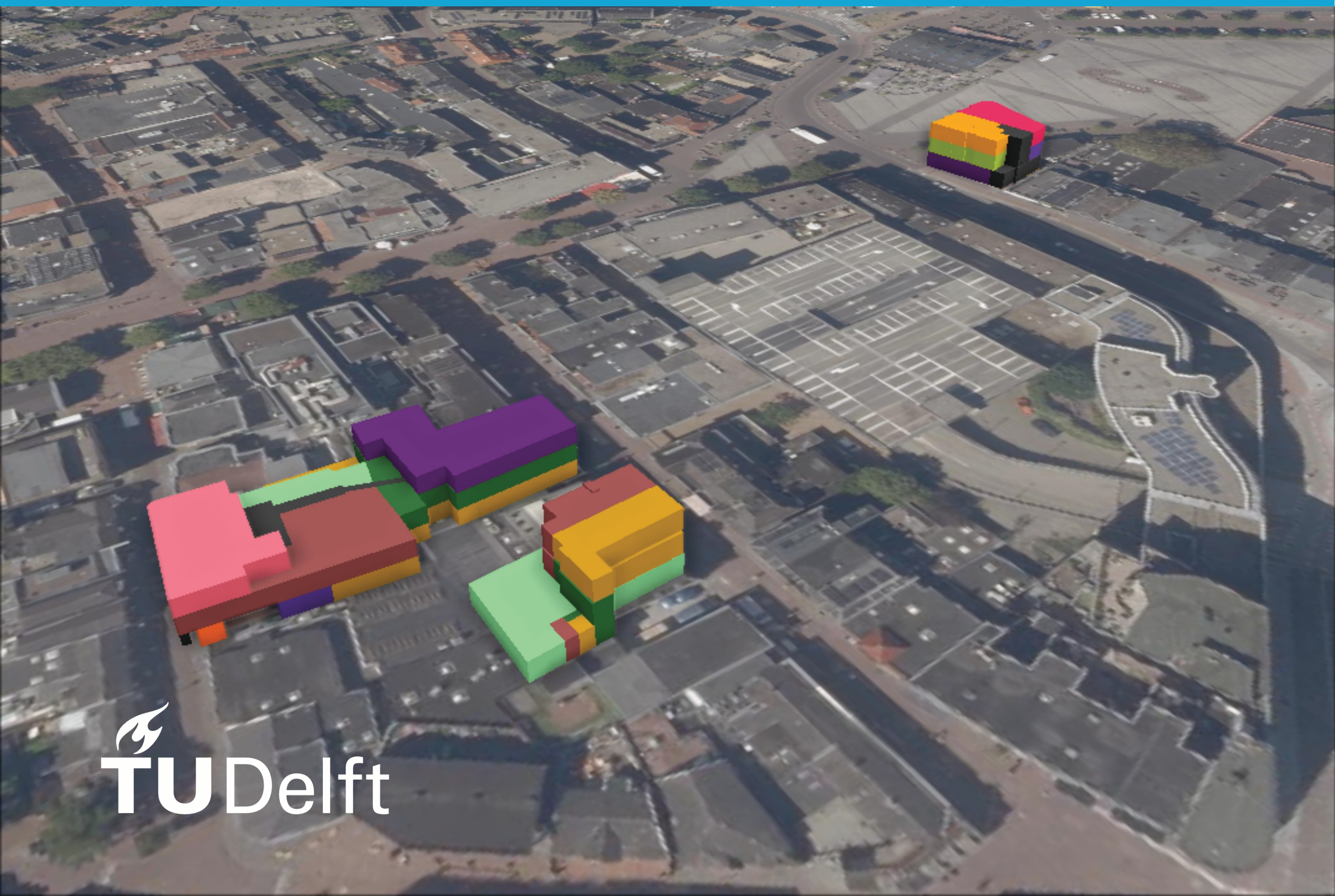
MSc thesis in Geomatics

Reconstructing legal 3D apartment models from 2D division drawings

Lotte de Niet

2025



TU Delft

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Reconstructing legal 3D apartment models from 2D division drawings

Emma Charlotte Jacoba (Lotte) de Niet

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A thesis submitted to the Delft University of Technology in partial fulfillment of the requirements for the degree of Master of Science in Geomatics

The work in this thesis was carried out in the:

3D geoinformation group
Delft University of Technology

Supervisors:	Prof.dr. Jantien Stoter
	2nd supervisor until March 2025 Amir Hakim Msc.
	2nd supervisor since March 2025 Dr.ir. Ken Arroyo Ohori
Co-reader:	Jasper van der Vaart Msc.
External Supervisor:	Dr. Bala Bhavya Kausika

Abstract

The continued growth in the complexity of apartment buildings, and the digitization of building processes have led to a rise in the use of BIM models during the architectural development phase. These models contain a lot of information, but their life cycle often ends once the building is constructed. However, this information can be used by the Dutch Cadastre, to bring legal building registration even closer to 3D reality. BIM based legal registration, researched under the name BIM Legal, is a key driver for this research.

Currently in the Netherlands, the separation of ownership is registered through notarial deeds that are managed by the Dutch Cadastre. This is accompanied by division drawings that indicate how apartments are split into private apartment units and shared spaces.

To develop a full BIM Legal registration, it is necessary to also look at buildings without a BIM model. In such cases, BIM Legal models could be derived from existing legal documents, specifically division drawings.

This research investigates the (semi-)automatic reconstruction of 3D legal apartment models from 2D vectorized division drawings. The proposed pipeline starts with already vectorized division drawings and applies shape-based georeferencing techniques, estimating storey heights, vertical alignment, and ends with generating 3D BIM Legal models.

The georeferencing methods tested achieved sufficient alignment across the 10 sample buildings. When outside spaces were included in the vectorized division drawing, it resulted in an average containment of 81.5%. When they were removed or non existing it resulted in 95.2% containment. Storey alignment relies on shape similarity and floor-to-floor matching, which performed well in typical cases but struggled with floors with low similarity to the floor below it. The accuracy of height estimation improves when cross sections are included in the division drawing. Otherwise averaged based on values retrieved from the 3DBAG. The resulting models conform to the BIM Legal standard, written in CityJSON format at a LoD1+. While the schematic nature of division drawings limits the achievable level of detail, and the geometric and positional accuracy, the models offer a valuable 3D visualization of private and shared ownership spaces. Improvements to the prior vectorization would also improve the accuracy and computation time of the 3D reconstruction. Large scale testing is necessary to research the potential incorporation of BIM legal models from division drawings with a complete BIM Legal registration.

This research not only advances the automation of BIM Legal models from division drawings, but also provides methods which can be applied in other 3D reconstructions, such as georeferencing polygons with a reference to a cadastral dataset.

Keywords: BIM Legal, 3D reconstruction, division drawings, apartment splitting, georeferencing

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Acronyms

2D Two-Dimensional.

3D Three-Dimensional.

API Application Programming Interface.

BAG Basisregistratie Adressen en Gebouwen.

BGT Basisregistratie Grootschalige Topografie.

BIM Building Information Modeling.

BRK Basisregistratie Kadaster.

CAD Computer-Aided Design.

CRS Coordinate Reference Systems.

DBSCAN Density-Based Spatial Clustering of Applications with Noise.

GIS Geographic Information System.

GoF Goodness of Fit.

ICP Iterative Closest Point.

ID Identifier.

IFC Industry Foundation Classes.

IoU Intersection over Union.

JSON JavaScript Object Notation.

KKN Kadastrale Kaart Next.

LoD Level of Detail.

OGC Open Geospatial Consortium.

PDF Portable Document Format.

RQ Research Questions.

RRR Rights, Restrictions, and Responsibilities.

SVG Scalable Vector Graphics.

WOZ Waardering Onroerende Zaken.

1. Introduction

The trend of urbanization of the last decades and population growth have led more people to move to dense urban areas (Broitman and Koomen, 2020). According to the Kadaster (2023), sales for apartment buildings have increased compared to other types of housing. These apartment buildings have multiple owners registered in the cadastral registration.

Figure 1.1.: Example of a complex building, including apartments, adapted from Choinowski (2021)

As the complexity of apartment buildings and their management grows, so does the need for more advanced tools to support their design, construction and legal administration. One of those tools that has been gaining popularity is BIM (Bryde et al., 2013) in which building complexes are modeled in detail for design and construction purposes. These models can be utilized across various levels of detail and applications. They enable the creation of 3D models using open standards like Industry Foundation Classes (IFC), the support of construction analysis, design, and visualization throughout the construction process (Biancardo et al., 2020) (Azhar, 2011).

To extend the usability of BIM after construction, particularly for legal and cadastral purposes, the BIM Legal model was developed (Stoter et al., 2024). This framework enriches existing BIM models by defining legal ownership spaces as 3D volumes using IFC standards.

These spaces are grouped into legal units, private and shared, enabling the visualization of ownership in buildings, particularly apartment complexes.

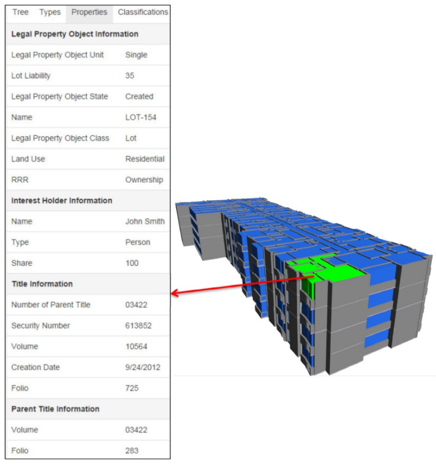


Figure 1.2.: Legal Information in a BIM model, adapted from Atazadeh et al. (2017)

While the design and construction of new buildings are increasingly done via the creation of BIM models, existing buildings often are not. However, many buildings exist for which a BIM model is not available, especially buildings that were constructed before the BIM was commonly implemented. Therefore, a reverse process is needed, in which BIM Legal models can be created from existing legal information about buildings. This would provide data interoperability and possibilities for data-supported solutions for the management and legal registration of existing buildings, for which BIM models do not exist.

A possible data source to generate these models from, are notarial deeds. Apartment units are established via a legal ownership document called a *splitsingsakte* (notarial deed), drawn up when a building is formally divided into apartments. This document maintained by the Dutch Cadastre, "Het Kadaster", defines the number of apartment units and their layout. The deed also legally establishes various Rights, Restrictions, and Responsibilities (RRR), such as apartment ownership rights, shared property responsibilities, and use limitations.

It also contains a mandatory *splitsingstekening* (division drawing), which shows the private and shared spaces in the building through 2D floor plans. Figure 1.3 shows an example of such a division drawing These drawings serve as legal references when ownership changes and are publicly accessible. However, they are often complex, especially in apartment buildings where units can spread over multiple floors, and multiple owners.

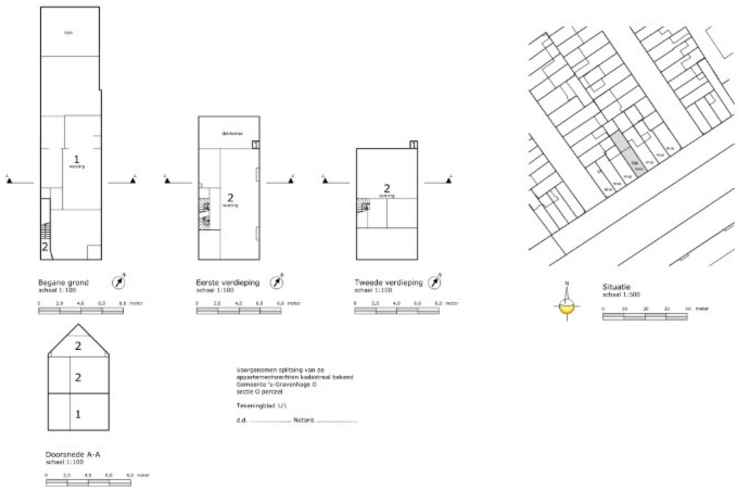


Figure 1.3.: Example division drawing

While the focus of BIM Legal is initially on deriving division drawings from the BIM models, there is growing interest in the reverse of this process for existing buildings, using 2D notarial drawings as a basis for generating 3D BIM Legal models. As building complexity increases and 3D building information becomes more widely used, 3D visualization and cadastral registration would offer advantages such as accuracy and clarity (Stoter et al., 2017). In the long term, the 3D BIM Legal models could replace the 2D drawings as source for legal property registration.

Currently, there is no open solution available for automating the conversion from division drawings to 3D BIM Legal models, which is needed to reduce time and cost when converting large numbers of deeds. While previous research has tackled similar 3D reconstruction processes, from inputs such as Computer-Aided Design (CAD) architectural drawings or point clouds, a full pipeline to reconstruct 3D ownership models from notarial deeds does not exist.

To address these issues (1. Complexity of analyzing deeds of apartments in 2D, 2. Lack of BIM models of existing buildings, 3. Lack of an automated reconstruction process), this research focuses on the conversion of 2D division drawings into 3D BIM legal models, as automated as possible.

This research is a collaboration with the Dutch Cadastre and builds upon their previous work, which explored the potential for deriving 3D models of apartment rights from division drawings. While the vectorization technique to automatically digitize the notarial deeds was promising, there were challenges, mainly: automating the georeferencing process, and addressing the differences per division drawing.

The goal of this study is to develop an, as far as possible, automated solution to generate BIM Legal models from 2D division drawings, making it possible to model and visualize ownership in 3D for existing buildings for which no BIM data is available. This process starts with vectorized division drawings as retrieved from the Cadastre and involves georeferencing using shape alignment techniques, estimating building heights, and structuring 3D models according to the BIM Legal standard.

By developing such a process, this research contributes to the field of Geomatics by investigating how legal division drawings can be georeferenced through spatial alignment techniques and transformed into 3D models of apartment ownership, contributing to the relatively new BIM Legal standard. In doing so, the research also offers practical guidelines for improving the vectorization of division drawings prior to 3D conversion. Additionally, the developed process can benefit other fields, such as the application of georeferencing techniques to architectural floor plans and supports broader data integration within BIM Legal.

1.1. Research Questions

The objective of this research is to develop a (semi-)automatic method of reconstructing 3D BIM legal apartments from 2D vectorized drawings of division. The resulting BIM models should be accurately georeferenced, extruded to a certain height to obtain valid 3D objects, and encoded according to BIM Legal standard. This research will identify valuable information in existing legal documents, or the lack thereof, that is necessary for the 3D reconstruction, for instance, by making use of the north arrow or the apartment cross section drawing. This knowledge can be used to improve the pipeline in the future by improving the prior vectorization. The topic is further divided into the following Research Questions (RQ):

- **Georeferencing**
  - **RQ1:** What data from the division drawings can be used to support georeferencing, and how valuable is each data type?
  - **RQ2:** Which initialization and optimization techniques are most suitable for aligning the division drawing footprints with the building footprints in the Basisregistratie Grootschalige Topografie (BGT)? What is the achievable georeferencing accuracy?
- **3D Reconstruction**
  - **RQ3:** What data from the division drawings can be used to support 3D reconstruction, and what is their value?
  - **RQ4:** How can floor heights be estimated from division drawings, and how can the floor plans be accurately positioned in 3D space?
- **BIM Legal**
  - **RQ5:** How can the generated data be structured according to the BIM Legal data model? What information is required to produce a valid BIM Legal model?
  - **RQ6:** How can the vectorization of division drawings be improved to support automated 3D reconstruction? How well do the resulting models integrate with the BIM Legal standard?

1.2. Scope

The focus of the study lies in the exploration of methods to accurately georeference and reconstruct the 3D apartment models from division drawings, with the goal of producing an automated workflow as much as possible. The scope of this research is defined by the following boundaries:

- The research assumes the division drawings have been vectorized. This step has already been researched during previous research by the Kadaster, which led to the development of VeCToR (Franken et al., 2021). Recommendations for the improvement of the VeCToR application based on the research results will be discussed, but not implemented.
- Except for the splitting of apartments into separate private units, modeling of the RRR's is not considered, as this is not part of the first phase of BIM Legal (Stoter et al., 2024).
- The question of whether division drawings are suitable or appropriate input for BIM Legal is out of the scope. This research merely focuses on how they can be implemented in a reconstruction process. However, outcomes may influence future decisions on their suitability.
- The extent to which the full workflow will be automated, depends on the accuracy that can be achieved without human intervention. Manual adjustment may be necessary.
- The use of aerial or street view imagery to add more details in the 3D reconstruction process will not be considered, as imagery linked to the apartments on a large scale is unavailable and as this still has many open issues, deserving a research on its own.

1.3. Outline

The research follows the following structure:

- **Chapter 2 - Background**: The second chapter provides background information of this research. This includes the motivation behind the research through previous work by the Kadaster, and the notarial deeds with division drawings are elaborated on.
- **Chapter 3 - Literature Review** : This chapter reviews relevant literature for the separate steps in the 3D reconstruction process. It also provides a deeper insight into BIM Legal.
- **Chapter 4 - Methodology**: Next, the methodology chapter presents the chosen techniques for georeferencing and 3D reconstruction. In addition to the standard workflow, alternative procedures for complex cases are also researched.
- **Chapter 5 - Tools and Datasets**: This chapter describes the datasets and tools used in the research. It also provides details on the cadastral data sources.
- **Chapter 6 - Results**: The results chapter presents the outcomes of the experiments. Each component of the pipeline is evaluated, quantitatively and qualitatively. The final version of the 3D reconstruction pipeline is also described.

- **Chapter 7 - Conclusion and Discussion**: Finally, the research findings are summarized and the practical applications are discussed. It reflects on the limitations of this research, as well as on areas for future research.

2. Background

Spatial data related to property is managed and collected by a central cadastral organization in the Netherlands, namely the Land Registry and Mapping Agency, or "Het Kadaster". They also produce and provide the topographic mapping at various scales in the Netherlands.

This chapter discusses the role of the Kadaster, and their previous work on digitizing and reconstructing apartment rights in 3D. It also presents background information on (3D) apartment rights, the notarial documents that define them, and the division drawings attached to those documents. Finally, related research into 3D property rights is summarized.

2.1. Apartment Rights and Division Drawings

One of the real estate rights registered in the cadastral registration is the ownership rights of apartments. This is described through notarial deeds. When a property owner wants to establish apartment rights (divide a building into separate legal units), a notarial deed of division must be created by a notary. They are then submitted to the Kadaster, which registers the deed in the public registry.

As summarized by Meulmeester (2019), apartment rights are defined shares of a property that grant rights of private units, and are formally established through a notarial deed. These are also known as *splitsingsaktes*, which split a building into separate rights and includes both a written description and a drawing.

Since 1973, the deed of division must include a *splitsingstekening* (division drawing), which shows the legal division of space within a building in a plan view (Bouwkundig Adviesburo R.O.B., n.d.). These drawings are schematic representations of legal ownership, not architectural floor plans. That means they depict legal spaces and not physical boundaries like walls, unless those boundaries happen to coincide. In the drawings, thick lines indicate boundaries of private units, remaining units in thin lines show shared parts (figure 2.1). Each apartment, whether a single legal space or a collection spaces, is identified by a unique apartment index.

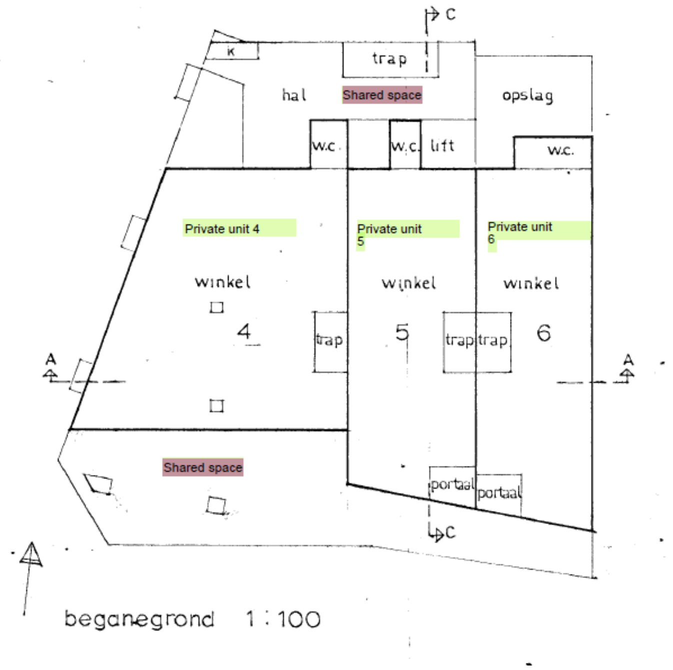


Figure 2.1.: Private spaces enveloped by thick lines and the remaining shared space

Appendix A shows a full page example of such a division drawing.

Over the years, the format requirements for these drawings have changed. Since 2006 the requirements by the Kadaster for these drawings have become more strict, not accepting hand-drawn division drawings anymore (Bouwkundig Adviesburo R.O.B., n.d.). Although, already submitted, outdated drawings are still present.

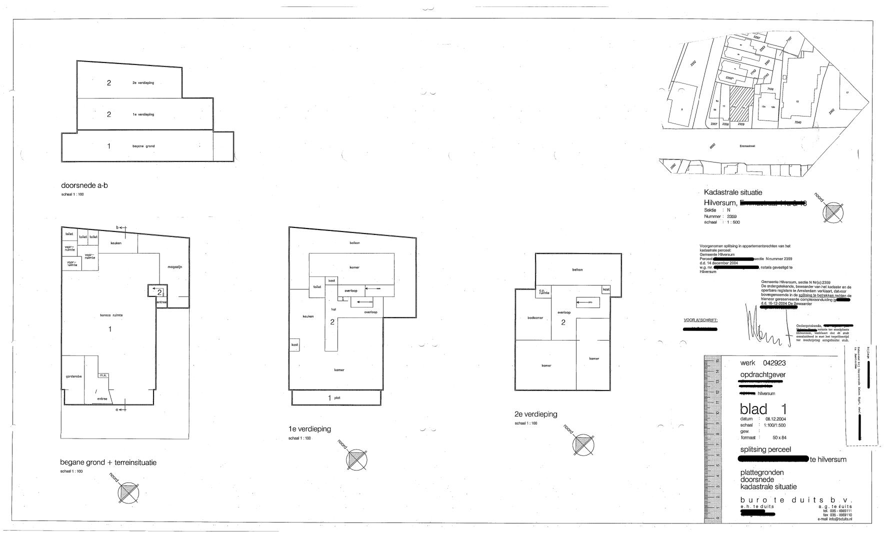
The division drawings require certain elements according to Het Kadaster (2019):

- A north arrow
- A scalebar
- The plot Identifier (ID) (*perceelnummer*)
- The shared spaces are indicated with thin lines, the apartments with thick lines and an apartment index
- A situational drawing

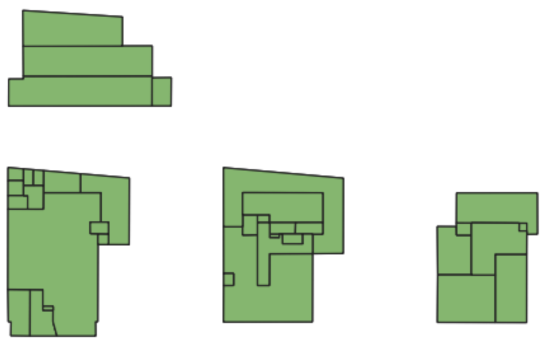
Many drawings also show one or more vertical cross sections that aid in providing an overview of the division of apartments, although a cross section is not mandatory.

2.1.1. Division Drawing Data Acquisition

The input division drawings used for this research were acquired through Kadaster. The starting data is the output from their pilot research as described in section 2.2. This includes 10 vectorized division drawings in JavaScript Object Notation (JSON) format, as well as the original Portable Document Format (PDF)s of the scanned documents. Once the JSON files are read into a geospatial database as described in section 4.1.1, the vectorized data can be visualized as in figure 2.2b.



(a) The original division drawing



(b) Vectorized division drawing

Figure 2.2.: Comparison of the original and vectorized division drawing

Each space also has included attributes and is shown in figure 2.3:

- room: a space index
- *verdieping*: corresponding to the text below the floor plan indicating the storey in which the space is located
- *appartement*: an apartment index
- *ruimte*: corresponding to the text that is sometimes included in the space, indicating its function.

However, the vectorization of these items in the division drawings did not always work properly and resulted in some storeys missing their label. It should also be noted that the cross section drawing never linked to its corresponding text, despite it being present in the PDF.

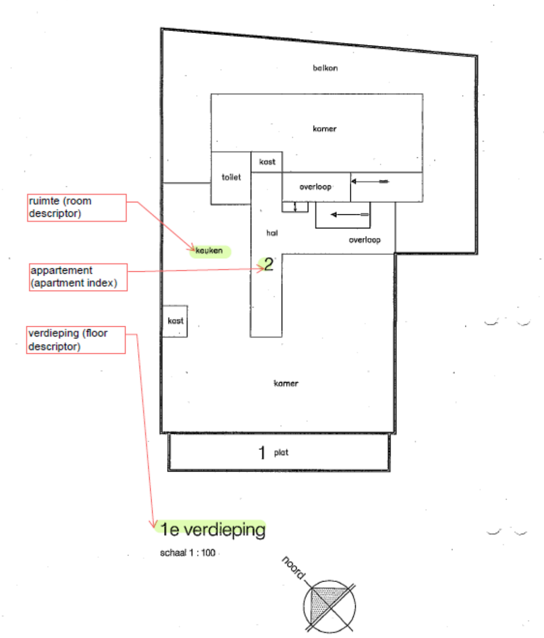


Figure 2.3.: Attributes of the spaces

In order to relate the geometry from the division drawings to real-world coordinates, they must be georeferenced. This is addressed in the methodology (chapter 4), where external spatial datasets, mainly the BGT, are used as reference geometries for alignment.

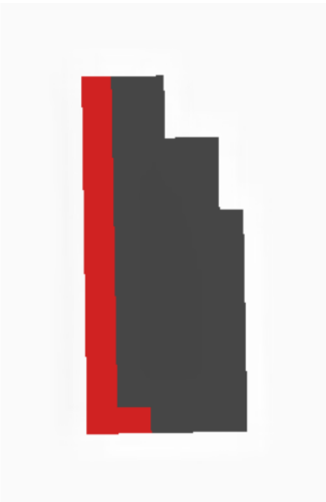
2.1.2. Data Requirements

- Given the schematic nature of the division drawings, it must be noted that the resulting 3D models are also schematic in character. These models are not suitable for precise measurements, nor are the division drawings themselves geometrically precise. As such, the generated BIM Legal models serve to represent legal representations in space, not accurate physical geometries.

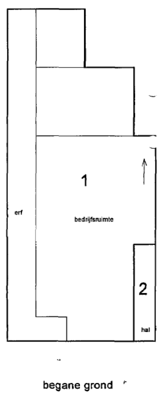
- In addition, the researched methods on georeferencing and 3D reconstruction add another level of uncertainty. As such, it is a requirement for the 3D models to include a measure of accuracy in terms of georeferencing (positional accuracy).

- To preserve the legal interpretation embedded in the geometry of the division drawings, distortions must be avoided. Only affine transformations, those that preserve relative structures, are considered for alignments and transformations.

- It is also important to note that division drawings may include not only interior apartment units but also outdoor spaces, such as gardens, balconies, and driveways. They have been removed during vectorization for some, but not all building datasets (2.1). whether private or shared, these are relevant to the legal subdivision of property and therefore should be vectorized. However when they are, they do not always correspond to the geometry in the reference dataset used for georeferencing, the BGT. This dataset provides building footprints and includes only the part of a building that physically touches the ground, leading to potential misalignments between the geometry in the division drawing and the BGT footprint. Figure 2.4a provides an example of correctly vectorized outside space, while figure 2.5a does not.



(a) Building correctly including the *erf* (parcel) geometry (in this case also labeled)

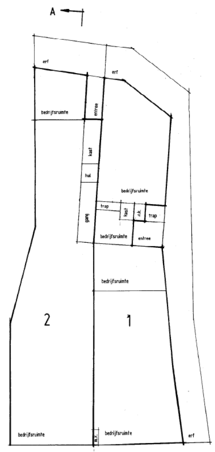


(b) The corresponding division drawing

Figure 2.4.: The *erf* geometry and its representation in the division drawing.

- Other differences between the division drawing and BGT may occur due to: division drawings being abstract representations rather than geographic accurate footprints; buildings having undergone modifications after the division drawings were created; a difference in scale; or noise from either the drawing itself (e.g. in hand-drawn division drawings) or the vectorization.

(a) Incorrectly no outside space



(b) The corresponding division drawing

Figure 2.5.: No outside space being vectorized despite it being present in the drawing.

2.1.3. Completeness

The completeness of the already vectorized division drawings is shown in table 2.1. Though not required, half of the division drawings include a cross section. This can provide valuable information regarding the storey height. Two additional drawings included a cross section in the PDF, but this was not vectorized. There does not seem to be a correlation between the year the drawing was registered, and the inclusion of a section.

Table 2.1.: Completeness of vectorized division drawings

Drawing ID	Drawing Year	Has Section	Storeys Correctly Labeled	Outside space removed
0555\0556	2002	Yes	Yes	Yes
1878\1879	-	Yes	Yes	N.A.
1882	2009	No	Yes	No
2359	2004	Yes	Yes	Yes
2643	2007	No	Yes	No
2848	1980	No	Yes	Yes
3211	2007	No	Yes	N.A.
3723	2002	Yes	No	No
4216	2006	No	Yes	Yes
9252	2013	No	No	No
Total		5/10	8/10	4/10

The storeys are correctly labeled if the storey geometry refers to the *verdieping* text attribute.

2.2. Kadaster Previous Work

The Kadaster has carried out a pilot research on creating 3D models from division drawings. This study builds upon another application developed for the Kadastrale Kaart Next (KKN), called VeCToR. For this application, AI was trained to vectorize and georeference 2D field sketches available as PDFs, in order to re-align a cadastral map (Franken et al., 2021).

The pilot on 3D reconstruction from division drawings utilized and adjusted the vectorization method to detect closed line sequences and store these geometries as "rooms". The AI model was trained to identify apartments by recognizing the thick lines and numbering used in the division drawings to distinguish individual units. During vectorization, each room is recognized and is associated with its descriptive text like "kitchen", and the corresponding apartment number, as described in section 2.1.

The buildings were manually georeferenced using QGIS and aerial imagery. The storey heights were determined as an average based on the total building height The storey polygons were then extruded to a single height value (Baving et al., 2023).

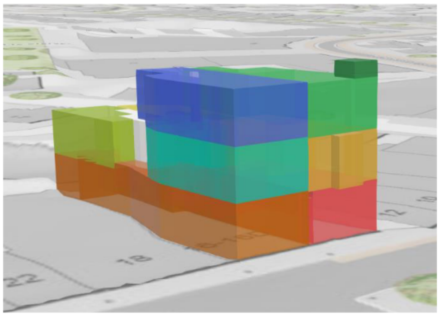


Figure 2.6.: A result of the 3D visualization of apartment rights, colored according to their apartment number. (Adapted from: Baving et al. (2023))

The shapefile results of the previous work by the Kadaster on manually georeferencing and 3D reconstruction are also available.

2.3. 3D Property Rights

The use of 3D for property management and visualization has become an increasingly popular topic of research for cadastral systems. Especially for complex buildings like apartments, 3D can provide clarity in the division of property. In this section, several studies on 3D cadastral legal property rights are reviewed.

Döner and Şirin (2020) reviewed the use of 3D models for apartment representations in Turkey, focusing on the transition from a 2D to a 3D cadastral system. Their method involves creating LoD2 models from photogrammetric data, and then providing more detail and interior spaces based on architectural projects. As they compare in their research, the Netherlands 3D reconstruction from division drawings has the advantage of being connected to the 2D cadastral objects and having a distinction between legal and physical spaces.

In the Netherlands, Stoter et al. (2017) explored the registration of 3D legal volumes, which is especially relevant in situations with multiple owners. This includes the right to an air space like a view, but also apartment rights. The investigation of real world cases proved that the 3D visualization provides better insight into the ownership in case of multilevel ownership.

Also in the Netherlands, a study was done by Broekhuizen et al. (2025) to assess the value of reusing real world BIM models for 3D cadastral registration. Various studies had been done before based on specifically adapted BIM models, but not on real world BIM models. They concluded that these models lack a link to their legal units and attributes to georeference. However, this link to the legal units is present in the division drawings, as well as a connection to the parcel for georeferencing.

3. Literature Review

Gimenez et al. (2015) reviewed the available solutions for reconstructing 3D BIM models of buildings from both on-site acquisition and from building documentation. Herein, the use of 2D paper plans of these buildings was identified as being most promising, due to their low cost, high availability, and high accuracy, though dependent on the completeness and reliability of the plans themselves.

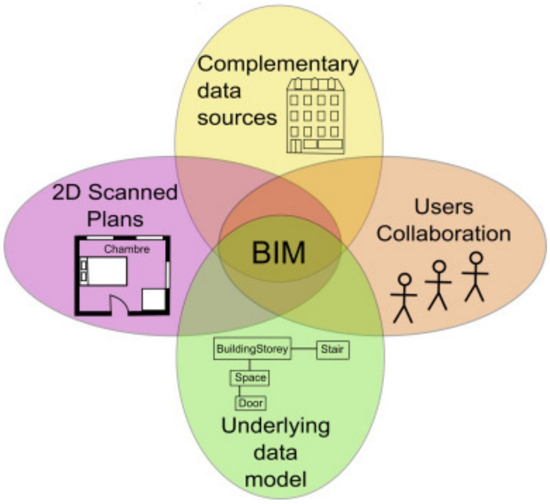


Figure 3.1.: Potential topics for future research, adapted from Gimenez et al. (2015)

They also name several topics for future research, as seen in figure 3.1. These topics closely align with this research: the use of additional datasets as a complementary data source, the incorporation of user feedback through manual verification, and the use of a simpler compatible data model. Instead of using the 2D scanned plans as proposed in the review of Gimenez et al. (2015), this research will focus on the use of 2D scanned division drawings. These plans are readily available by the Kadaster in huge amounts, and will provide the basis for the legal 3D model. The underlying data model is in this case the BIM Legal model, which simplifies the data structure of the BIM models.

A company called Coders Co. (2025) has developed a semi-automatic tool to reconstruct 3D models from division drawings. Their goal was not to reconstruct BIM Legal models, but to showcase building valuation in 3D. This property valuation system is called the Waardering Onroerende Zaken (WOZ) and is based on building registration in the Basisregistratie Adressen en Gebouwen (BAG). Each reconstructed unit then corresponds to a WOZ object. However, their application and development process are not open and therefore will not be taken into account in this study.

How the 3D buildings are reconstructed depends heavily on the input. For example, if CAD drawings are available, measurements can be derived from the model itself and can be used to extrude the geometries. Point cloud data typically requires post-processing, such as segmentation, simplification, and surface reconstruction to generate building models. Since there is no known full reconstruction method using division drawings as input, this research investigates the individual steps of the workflow separately. This starts by georeferencing and floor alignment, which are both 2D shape alignment problems, followed by estimating the storey heights and reconstructing the spaces in 3D, and lastly encoding the data in accordance to the BIM Legal data model and its visual representation.

3.1. 2D Shape Similarity and Alignment

Integrating the geometry of the division drawings with a corresponding georeferenced cadastral dataset is required for their legal registration as BIM Legal model.

This research includes two shape alignment problems. Firstly, the ground-floor geometries must be aligned to the Base Register Large-scale Topography (BGT), which represent the physical boundaries of the apartment building at ground level. As described in chapter 5, there can be differences between the geometries in the BGT and the division drawing. This means that the used methods must find the best possible alignment.

Secondly, each additional storey must be translated to form a stack corresponding to the 3D positioning in the apartment building.

Both these tasks revolve around the common question of how similar planar shapes are, and what transformations they require to best align. Answering these questions requires algorithms for *shape alignment* and metrics for *shape similarity*.

To preserve the geometry of the division drawings, only affine transformations have been researched.

Many alignment techniques (e.g. Minkowski distances, Iterative Closest Point (ICP), or Procrustes analysis) rely on a point-to-point correspondence between the input polygons (Veltkamp, 2001b), (Pizarro and Bartoli, 2011). In practice, the number of vertices in the division drawing and BGT do not match. Instead, shapes can be compared through their boundaries.

3.1.1. Shape Similarity Metrics

Hausdorff Distance: As described by Veltkamp (2001a), when there is no one-to-one correspondence between points, the Hausdorff distance is often used. The Hausdorff distance can be used as metric to minimize the distance between the boundaries of the two geometries. It is the maximum distance between the closest points of the geometries (Ryu and Kamata, 2021). Since this method is based on the contours, the accuracy depends on how similar the contours are.
The undirected Hausdorff distance takes into account the distances from A to B, and B to A. The directed Hausdorff distance only considers the distance from A to B. Due to the directed Hausdorff distance being asymmetric it is not considered a valid metric (Laxhammer and Göran).

Fréchet Distance: Similar to the Hausdorff distance is the Fréchet distance. Unlike the Hausdorff distance, which only considers the closest point at any position, the Fréchet distance looks at the paths as a whole, and measures the distance between them, as they are traversed. This makes it useful when comparing curves that follow a certain direction. (Veltkamp, 2001a).

Shape Similarity: Another simpler metric that was used to compare similarity between polygons is the shape similarity as described by Morlighem (2021). It is the percentage of overlap between the geometry and its reference with a certain buffer distance. Compared to the previous metrics, this metric takes into account the full boundary instead of only the worst case distance.

Turning function: The turning function is used to compare polygon contours by analyzing their turn angles along the boundary. It minimizes the differences in shape by adjusting the rotation angle (Veltkamp, 2001a). The turning function can be used as metric by minimizing the distance between the two turning curves, by adjusting the rotation. This minimum distance is then used as value to optimize. This metric is translation and scale invariant (Ruiz-Lendínez et al., 2017) and heavily depends on the similarity of the boundaries. It was also considered by Morlighem (2021) for comparing shapes after automatic extraction to a ground truth, but disregarded due to its sensitivity to outliers.

Area-Based Overlap

Due to the possibility of the main geometries barely matching the reference geometries, other metrics are investigated, which maximize the area of overlap. This approach can handle cases where polygons do not have closely matching contours, but may struggle with properly aligning local variations, as it prioritizes the total overlap between the division drawing geometries and the BGT.

Goodness of Fit: This metric measures how well polygons match by calculating the amount of overlap between them. It takes into account the proportion of the geometry of the division drawing that correctly overlaps with the reference BGT. (Hargrove et al., 2006).

Intersection over Union: The Intersection over Union (IoU) also measures the overlap between geometries by dividing the area of their intersection by the area of their union. This metric provides a more global assessment by evaluating how well both geometries fit into each other (Kippers et al., 2021).

3.1.2. Shape Alignment Techniques

Optimizing a Metric: As described, the alignment of the division drawing and the BGT can be performed through optimizing a similarity metric. This can be achieved using an exhaustive grid search, where the geometries are translated, rotated and scaled. After which the similarity metric is used to score each alignment iteratively until the maximum score for the metric is found, yielding the best transformation.

Edge Matching: Edge matching is used by (KKN) to match and align field sketch polygons to reference polygons (Franken et al., 2021). This method focuses on aligning matching edges between the BGT and division drawing geometries. However, this method is limited when geometries differ significantly. For example if one polygon contains many small edges instead of one long edge (Long et al., 2016).

3.2. Storey Height Estimation

Estimating storey heights is a necessary step for 3D reconstruction when height information is not available, as is the case with division drawings. Several approaches have been proposed in previous research, depending on the type of input and goal of the model.

Roy (2022) notes that while non-residential buildings display more variation in storey heights, residential buildings such as apartment blocks tend to be more consistent, allowing for the use of a uniform estimate. The focus of this research was to determine the amount of storeys. A common method in the Netherlands involves using the 70th percentile of the buildings point cloud height from the 3DBAG dataset, and dividing this by the standard floor height of 2.65 meters. As this is the minimum storey height in the *bouwbesluit* (Dutch building regulations) for habitable spaces (Roy, 2022).

An alternative, more geometric approach is proposed by Boeters et al. (2015), who also estimate the storey heights based on the building height, but then refine this by snapping to distinct changes in the external building geometry. This method assumes that distinct changes in the exterior often reflect floor changes in the interior.

Architectural based sources often contain height information directly in the plans. Lewis and Séquin (1998-09-01) use reflected ceiling plans, containing textual height annotations, which can be used to extrude the geometries. Similarly, Chandler (n.d.) reconstructs 3D models from Scalable Vector Graphics (SVG) architectural drawings, without textual information, requiring user input for the scale and storey height.

Indoor scans provide another method of estimating storey heights. Turner et al. (2015) derive the storey heights from a mobile indoor scanned point cloud of a multistorey building. By creating a histogram of the z-axis, the local peaks indicate floors and ceilings. Okorn et al. (2010) used a similar method, but used voxels instead of the points for the histogram, so that dense areas do not necessarily create peaks.

Since the storey heights are not included in the division drawings, it will be required to estimate the heights. The geometric approach of Boeters et al. (2015) based on the exterior from the 3DBAG presents a viable option, though based on estimates from the exterior. However, as shown in part 2.1, often the division drawings include a section drawing. This section, when scaled, can provide a more accurate storey height estimate, which also include interior changes in height and basements that are not visible from outside.

3.3. Level Of Detail

Having georeferenced the division drawing footprints and estimated building heights, the next step is to construct the 3D building models themselves. This requires deciding on an appropriate level of geometric detail, for which the officially defined Levels of Detail have been examined.

The LoD defines the geometric complexity of a building model in 3D city models. Higher, more specific LoDs allow for more detailed and accurate analysis but also require more detailed source data. The concept of LoDs in 3D GIS was introduced by the Open Geospatial Consortium (2012) (Open Geospatial Consortium (OGC)) within the CityGML standard. CityGML 2.0 defines five LoDs, as seen in figure 3.2. These gradually increase in detail. However, these specifications did not provide minimum requirements in terms of geometry or semantics, leaving this up to the user.

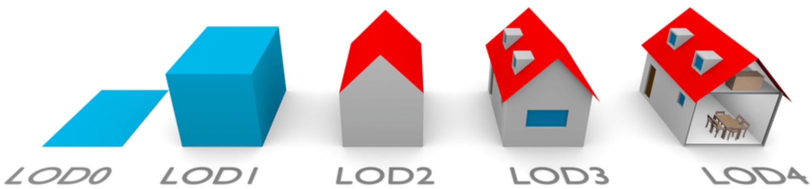


Figure 3.2.: The five LoDs of CityGML 2.0, adapted from (Biljecki et al., 2016)

Biljecki et al. (2016) proposed more detailed LoD specifications. These specifications allow for more practical use of the LoDs in 3D modeling, so that the 3D building models conform to more detailed requirements. An important dataset that incorporates these specifications is the 3DBAG dataset. The 3DBAG viewer includes the LoD0.2, LoD1.2, LoD1.3 and LoD2.2 (Peters et al., 2022)

- LoD1.2 represents building blocks with flat roofs, where the building is extruded from its footprint. This height is determined as the 70th percentile of the height points that represent the roof.

- LoD1.3 is similar but allows multiple extrusion heights within one building. Roof parts are modeled to single heights which are determined from the 70th percentiles of the height points on the corresponding roof parts.

- LoD2.2 includes an approximation of the roof structures which are modeled from the AHN point cloud.

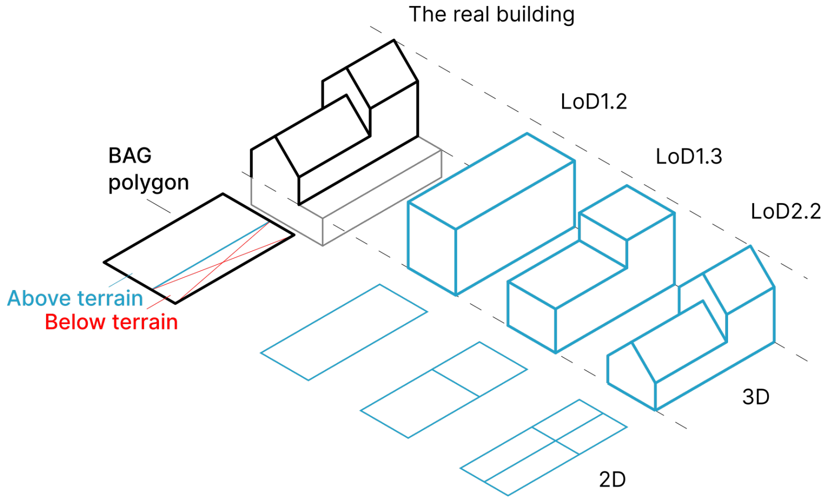


Figure 3.3.: 3DBAG LoD Layers, adapted from (Peters et al., 2022)

Interior Level of Detail While the OGC LoD definition purely describes the exterior geometry, there is also a need for interior modeling at different levels of detail, especially for use cases based on interior volume calculations. Kemec et al. (2012) proposed the idea of intermediate steps, such as LoD1.5 for modeling storeys, LoD2.5 for interior rooms, and LoD3.5 for apartments, to better support applications like disaster risk management. Building upon these developments, the concept of LoD+ was proposed by Boeters (2013) to better align interior LoDs with exterior LoDs in CityGML.

- LoD1+ includes simple extruded storey blocks inside the extruded LoD1 buildings (figure 3.4a.).
- LoD2+ includes roof structures and boundary surface thickness (figure 3.4b.).
- LoD3+ refines this further with the modeling of units, entrances and stairwells
- LoD4+ corresponds to full architectural interior modeling as is often used in BIM models

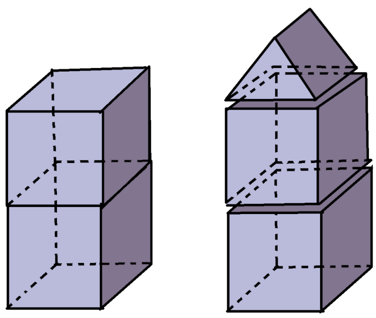


Figure 3.4.: LoD1+ and LoD2+

3.4. BIM Legal

The idea of using BIM as source for registering legal property rights in 3D has been explored in several studies. Early proposals in the Netherlands are based on the principle of deriving legal property information from BIM models, in order to register apartment complexes as 3D models (Meulmeester, 2019). This has been further developed as the BIM Legal data model (Stoter et al., 2024). The goal is to visualize the building ownership in a 3D model comprised of legal spaces.

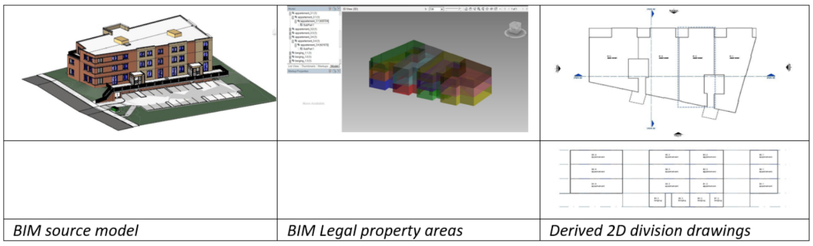


Figure 3.5.: BIM Legal and its derived division drawings Source: VDNDP Construction Engineers (adapted from (Stoter et al., 2012)

The move towards BIM Legal is largely driven by the limitations of the current handling of multi-level property rights. As discussed in (Stoter et al., 2017), the current handling of 2D drawings struggles to represent ownership in overlapping environments such as multi-level and multi-functional garages or towers. As mentioned by Broekhuizen et al. (2025), registering RRR directly in relation to the spaces within a BIM model would present a more precise and automated legal registration process. Guler et al. (2022) compared workflows in the Netherlands, Saudi Arabia and Turkey. They emphasize that missing or inaccurate modeling of legal spaces can cause errors in land share allocations and mention that the input BIM models should be in their as-built form, and enriched with legal properties.

BIM Legal is aligned with the buildingSMART's IFC standard, which is an open standard for BIM modeling. The main implementation idea of BIM Legal for apartment complexes is to use IFCSpaces to represent legal volumes. These grouped together form apartments. The paper (Stoter et al., 2024) outlines how apartment hierarchy can be mapped to an IFC schema via IDS. One of the main research areas for BIM Legal is the lack of georeferencing in IFC models. Noardo et al. (2020) notes that BIM models use local coordinate systems, requiring transformations into recognized Coordinate Reference Systems (CRS) to be able to integrate individual BIM models into their geographical contexts. Especially IFC2x3 files, which are widely used in practice, do not natively support newer georeferencing methods such as LoGeoRef50, which are only available in IFC4.

Experiments have been performed for the use of IFC as input for a legal 3D LAS and validating these BIM models (Broekhuizen et al., 2025). The data quality issues and resulting modeling guidelines will be taken into account in this research.

- Define all legal units as uniquely identifiable 3D volumes.
- Ensure all geometries are valid and free from inconsistencies.

- Avoid overlapping or gapped geometries by performing thorough geometric validation.
- Incorporate accurate georeferencing information to allow integration with 3D cadastral systems.
- Each *BIMLegalSpaceUnit* should include a property set with: the apartment index number, cadastral parcel number, complex number, space type, and the respective municipality.
- Use *BIMLegalSpace* to group units that belong to the same legal space (e.g., an apartment), instead of duplicating grouped volumes as additional *BIMLegalSpaceUnit* objects.
- Prefer using the IFC4 schema with embedded georeferencing attributes. If using older IFC 2x3 models, enrich them with attributes compliant with LoGeoRef30 and/or LoGeoRef40 to improve georeferencing accuracy.

As described by Stoter et al. (2024), during their phase 1 of BIM Legal for cadastral registration, the goal is to create BIM Legal models from existing BIM models, and then retrieve the 2D division drawings from them. In the future however, the goal is to have the 3D BIM Legal models replace the 2D drawings.

In this research, a different aspect of BIM Legal will be explored for existing buildings. This research focuses on the cases where there is not a BIM model, but instead a division drawing exists. By converting these 2D drawings to 3D BIM Legal models, also apartment buildings that have already been registered can be visualized in 3D and stored according to the same standard. In this case, a conversion from geo to the BIM Legal data model has to be made.

4. Methodology

This chapter presents the methodology developed to georeference vectorized division drawings and reconstruct them to 3D BIM Legal models. This process consists of three main components: (1) Georeferencing: 2D Alignment from initializing to optimization, (2) 3D Reconstruction: Floor Alignment and Height Estimation, and (3) BIM Legal creation (figure 4.1).

For the different steps in the process, several methods have been tested and compared to establish a mostly automatic process. The goal is to find a workflow that works in most cases, with alternatives for the most common exceptional cases. The evaluation and comparison of the different alternatives for each step are discussed in chapter 6.

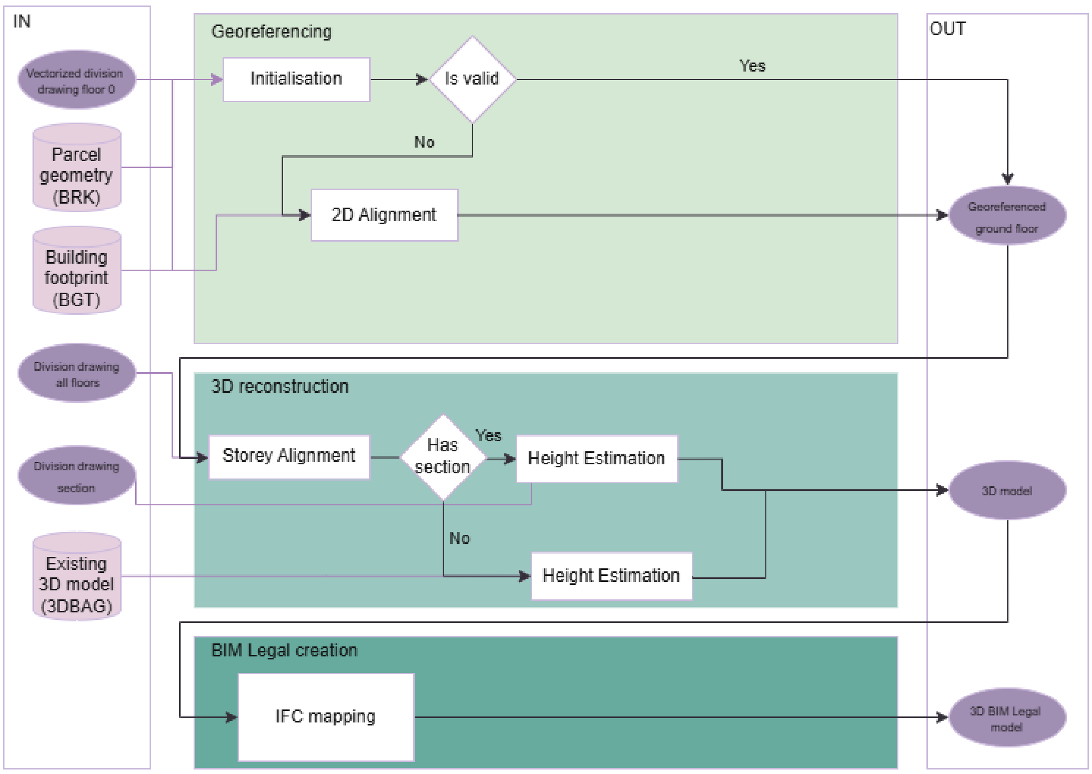


Figure 4.1.: Overview of the method flow and the used data

4.1. 2D Alignment and Georeferencing

The vectorized floor geometries extracted from the division drawings are initially positioned in a local coordinate system, corresponding to their placement on the division drawing. In order to integrate these geometries with geospatial data, georeferencing is an important step.

Each drawing includes a textual reference to the cadastral parcel on which the building is located. Based on this reference, the division drawing geometry can be linked to the corresponding building in the cadastral map, allowing for georeferencing through an alignment to this reference, thereby georeferencing the resulting BIM legal model.

The selection of the georeferencing methods was guided by three criteria:

- **Differences between sources**: Since the footprints from the division drawings can differ from the BGT geometries, methods were favored that can handle such inconsistencies and still provide a reasonable alignment.
- **Information availability**: Preference was given to methods that make use of the available data in the division drawings, such as north arrows and scale indicators, in order to stay close to the source material.
- **Automatic**: Methods that can be automated were favored.

4.1.1. Preprocessing

Before the alignment process can begin, the division drawings data must be converted into usable geospatial information. This involves several steps:

- Reading vectorized input: Each division drawing is stored as a JSON file containing vectorized representations of rooms and associated attributes such as the room label, apartment number and floor name. These files are parsed and converted into GeoDataFrames using Geopandas. The geometries are still stored in local coordinates.
- Extracting parcel identifiers: Parcel information for the involved apartment is included in the division drawing as text. Figure 4.2 provides an example.

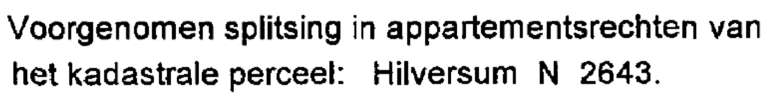

Voorgenomen splitsing in appartementsrechten van
het kadastrale perceel: Hilversum N 2643.

Figure 4.2.: Parcel identifier on the division drawing, stored as: HVS00 N 02643

This label identifies the cadastral parcel through:

- AKRKadastraleGemeenteCodeWaarde: The municipality code (HVS00), corresponding to the municipality (Hilversum)
- Sectie: The part of the municipality it is located in (N)
- Perceelnummer: The parcel identifier unique to this municipality section (02643).

These identifiers have been extracted during the vectorization process and were embedded in the filenames of the JSON files, associating each division drawing with its cadastral parcel data.

- Handling multiple parcels: Some division drawings refer to multiple parcels. This is the case when the apartment is located on multiple cadastral parcels. This was incorrectly vectorized, as always only one identifier was provided per drawing per file name. To address this, in these cases the additional parcel identifiers were added manually to the filename. Throughout the pipeline, it is taken into account that the input can include multiple parcels.

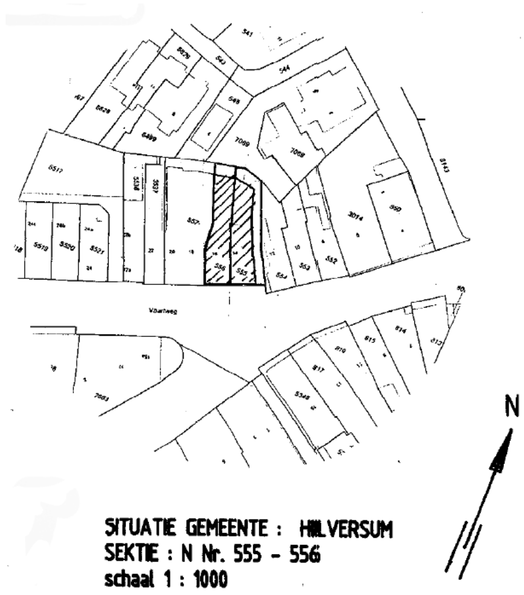


Figure 4.3.: A division drawing situation-sketch showing multiple parcels

4.1.2. Initialization

The division drawings are georeferenced by aligning them to their closest match in a current building database. This can be performed through the ground floor geometry detected in the division drawing, which corresponds to the building geometries in the BGT, as they reflect the building footprints at ground level. The retrieved parcel identifiers are used to retrieve parcel geometries, which can be used to acquire the BGT objects through spatial overlay, for alignment. The retrieval of the BGT is shown in image 4.4.

The parcel geometries themselves can be acquired from the Basisregistratie Kadaster (BRK) through*Kadastrale Kaart Application Programming Interface (API)* (Kadaster, 2025b), through their identifiers. The buildings located on these parcels are then obtained through the BGT. Since the *BGT Features API* (Kadaster, 2025a) only accepts bounding boxes as geometry input (not the parcel geometry), the bounding box of the parcel is used as the query parameter. Once the BGT geometries are obtained, any BGT building whose geometry does not sufficiently overlap (set to 2 squared meters) with the actual parcel polygon(s), are filtered out.

Finally, the remaining building geometries located inside the same parcel as the one in the division drawing are maintained for further processing.

Figure 4.4.: BGT retrieval

It is possible for these parcels to contain multiple buildings. In some cases they correspond to the same (number of) buildings in the division drawings, but it is also possible that more buildings are located on the parcel and thus selected from the BGT , than are included in the division drawing. This is taken into account when the alignment is optimized in section 4.1.3.

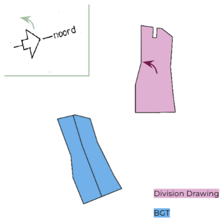
The initialization step aims to provide a starting point for the alignment process, reducing the complexity of optimization. It is assumed that the general shape (the outline) of the vectorized building ground floor should match with the footprint of the BGT, as both represent the footprint of the building.

Several candidate methods were considered for estimating initial transformation parameters.

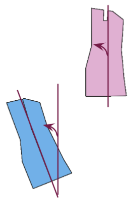
Rotation

The rotation step ensures that the division drawing ground floor geometry aligns with the orientation of the reference BGT footprint. Two methods were considered for estimating the correct rotation:

- **North Arrow Based Rotation:** The first method relies on using the north arrow on the division drawings. The retrieval of the orientation of this arrow could be possible using machine learning icon detection, during the vectorization step of the process. Once the arrow geometry is retrieved, its angle with respect to the vertical axis can be computed and used to rotate the vectorized drawing. For this research, the potential of the use of the north arrow was explored. The angles were manually collected based on the arc between the north arrow and 0 degrees, using Rhino (McNeel, 2023).



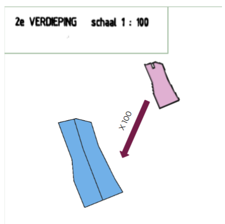
- **Azimuth Based Rotation:** The second method calculates the azimuth between the building in the division drawing and BGT. This is achieved by first computing the minimum bounding rectangle for each polygon. The line through their centers is then used to determine the direction of the polygon. The difference in angles between the reference BGT and the deed polygon is taken as the rotation angle required to align them.



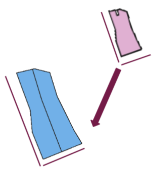
Scale

Secondly, the scale of the division drawing has to be estimated. Two methods were considered:

- **Text Based Scale:** When scale information is shown on the division drawings, such as a scale ratio text. This ratio can be applied directly to adjust the scale of the division drawing footprint. This method assumes that the scanned drawings preserve their original printed scale and that this attribute is linked properly to the corresponding storey.



- **Area Based Scale:** Alternatively, the scale can be estimated by comparing the areas of the reference BGT footprint and the division drawing polygon. The scale ratio is computed by dividing the area of the reference BGT by the area of the division drawing ground floor geometry. This method assumes that the building outlines in both datasets are similar at least in size.

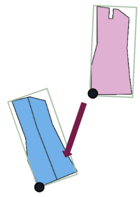


$$scalefactor = \sqrt{\frac{A_{\text{BGT}}}{A_{\text{division drawing}}}}$$

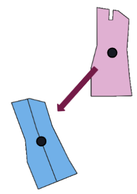
Translation

The translation is the last step, as the bounding box alignment relies on a similar rotation in the transformed and reference polygons.

- **Centroid Alignment:** This is the most straightforward method of initializing the translation. The vectorized polygons are translated so that their centroids coincide with the centroids of their corresponding BGT footprint. This method assumes that the overall shape is approximately similar.



- **Bounding Box Alignment:** This method outlines the bounding box of both footprints. The vectorized polygons are translated based on the lower left coordinates of the minimum bounding box of both geometries. This approach is considered because it is less sensitive to boundary similarity between the two footprints because it only considers the overall outer boundary.



4.1.3. Optimization

The objective of this step is to align the ground floor geometries shown on the division drawings closer to the the correct corresponding BGT footprint than the previous step. This can be done by optimizing the affine transformations to best fit the footprints. To find the optimal transformation, several optimization techniques were considered. The techniques as described in section 3.1 are researched in two section.

The first is an exhaustive method that utilizes polygon fitness metrics to find the optimal transformation. The other uses similarity of edges to find matching edges and use these as reference for the transformation. An overview of the researched methods for 2D alignment is given in figure 4.5.

The chosen methods include:

- The directed Hausdorff distance: Accounting for the worst-case distance from the division drawing to the BGT geometries.

$$h(A,B) = \max_{a \in A} \min_{b \in B} \|a - b\|$$

- The averaged Hausdorff distance: Unlike the directed variant, this metric takes into account all point-wise distances. Potentially allowing for a more balanced alignment.

$$\bar{h}(A,B) = \frac{1}{|A|} \sum_{a \in A} \min_{b \in B} \|a - b\|$$

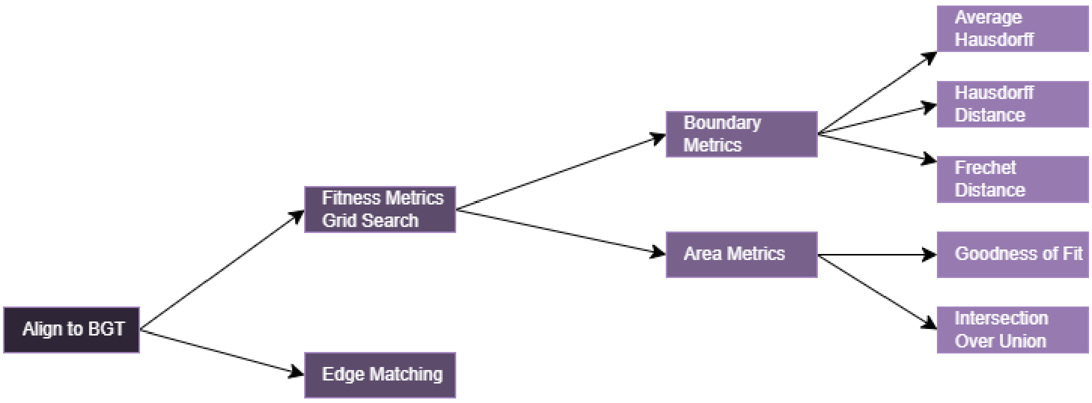


Figure 4.5.: Explored methods for 2D alignment

- The Fréchet distance: Measures the closeness between two curves by calculating the largest distance in A to the closest point in B. Suitable for comparing the overall structure of the shapes.

$$d_F(A, B) = \inf_{\alpha,\beta} \max_{t\in[0,1]} \|A(\alpha(t)) - B(\beta(t))\|$$

- The Goodness of Fit: Measures how well polygons overlap relative to their individual areas, favoring high intersection and low mismatch of the building geometry in the division drawing to the BGT building.

$$\text{Goodness of Fit (GoF)} = \left(\frac{\text{area}(A \cap B)}{\text{area}(A)}\right) \cdot \left(\frac{\text{area}(A \cap B)}{\text{area}(B)}\right)$$

- The Intersection over Union: The IoU measures the ratio of shared to total area, making it less sensitive to the division drawing.

$$\text{IoU} = \frac{\text{area}(A \cap B)}{\text{area}(A \cup B)}$$

As mentioned, point-to-point methods are not considered. Neither is the turning function due to the reliance and sensitivity to local similar boundary shapes, which is not necessarily the case. The shape similarity is also not considered for this alignment, because of the need for an existing similarity between the datasets.

As described in section 4.1.1, the process of retrieving the BGT buildings can cause multiple building geometries to be selected. Depending on the amount of geometries in the retrieved BGT dataset, and in the division drawing, several cases of alignment are possible, these are further described in section 4.1.4.

Exhaustive Search

To align the building polygons in the division drawing to the BGT footprints, a grid search based optimization approach was implemented. The goal of the alignment is to find the optimal transformation, including translation, rotation and scaling, to find the best match between the division drawing and reference footprint geometries.

Two types of metrics were combined, boundary and area based (figure 4.6), to account for both local contour alignment and global area overlap. This requires minimizing of the distance measure and maximizing of area overlap, in order to find the optimal transformation to align the division drawing footprint to the BGT footprint.

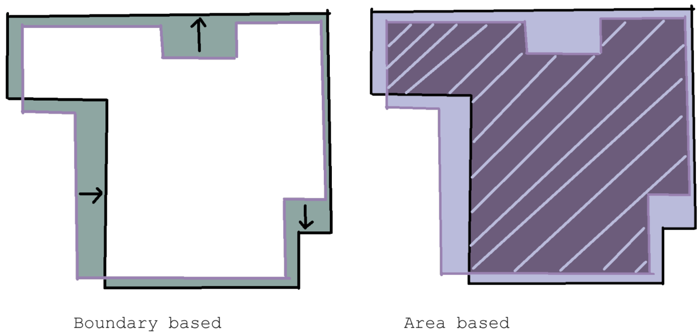


Figure 4.6.: Boundary-based and area-based alignment metrics.

Algorithm 4.1: GridSearchAlign(geometry, BGT_outline)

foreach *combination of scale s, rotation θ, and translation* (dx, dy) **do**
  transformed ← apply scale s, rotation θ, and translation (dx, dy) to geometry;
  CombinedScore ← $AreaMetric + BoundaryMetric$;
  if *score is better than previous best* **then**
    best_score ← score;
    best_transformation ← current parameters;
return best_transformation and transformed geometry;

The best result was determined by scoring each transformation using a weighted sum of the two metrics, which determines how well the building in the division drawing fits the BGT footprint. The area metrics already score a percentage amount of overlap, but the boundary metrics have to be normalized to return a score between 0 and 1.

$$CombinedScore = \alpha \cdot AreaMetric + \frac{(1-\alpha)}{1 + BoundaryMetric}$$

The values of these weights (α) were also explored. Both the quantitative and visual results were computed. For each alignment the metric values were logged and manually inspected in QGIS to inspect the quality of the fit, especially on rotation as this is poorly initialized. The results of these tests are shown in section 6.1.2.

The searchable transformation ranges are determined as follows:

- **Scale**: A range between 0.8 and 1.2 is chosen, with steps of 0.05. This range mainly accounts for minor differences between buildings in the division drawing and the BGT.
- **Rotation**: Due to the results of the initialization of the rotation (section 6.1.1), the search range cannot be limited if the north arrow is not detected. Therefore the full range of rotation angles is used (-180, 180), in 1 degree increments.
- **Translation**: The translation range was initially set to 2 meters on the horizontal and vertical axis. However, when exploring potential cases including multipolygons (section 4.1.4), the search range needed to change. It was made dynamic based on the largest distance between any two points in the division drawing geometry.

It should also be noted that for multipolygons, all transformations were applied uniformly, preserving relative distances between the polygons.

Edge Matching

In addition, edge matching was researched as a possible alternative to the exhaustive search. The edge matching features were chosen as to represent the edges, not their vertices.

The edges are matched based on the following criteria:

- **Midpoint Distance (4.7)**: Two edges are considered a potential match if the distance between their midpoints is below a certain threshold:

  $$\|m_1 - m_2\| < \tau_d$$

  where m_1 and m_2 are the midpoints of the edges, and τ_d is the distance threshold. Midpoints are used instead of endpoints as an average representation of the edge position.
- **Orientation (4.8):** The orientation θ of an edge is computed using its endpoints (x_1, y_1) and (x_2, y_2):

  $$\theta = \arctan 2(y_2 - y_1,\ x_2 - x_1)$$

  Edges are only matched if their orientations are similar.
- **Length (4.9):** The lengths of the two edges must also be close. The absolute difference should be less than a threshold τ_ℓ:

  $$|\ell_1 - \ell_2| < \tau_\ell$$

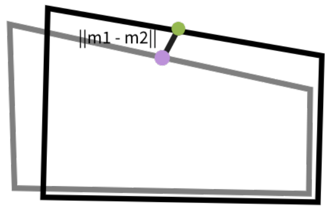


Figure 4.7.: Midpoint distance

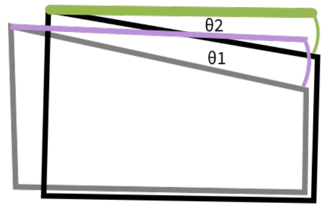


Figure 4.8.: Orientation

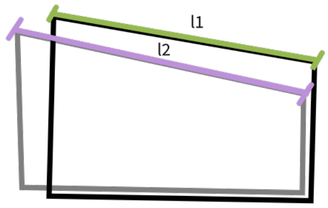


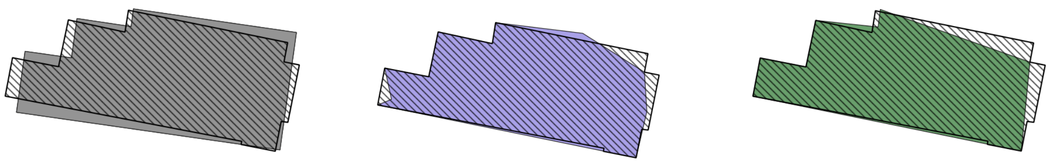
Figure 4.9.: Length

After the edges are matched, the transformation for the division drawing edges to perfectly align with their corresponding BGT edges are estimated. And the whole geometry is transformed.

Additionally a test was performed with different features. This only takes into account the angle between two neighboring edges and edge length. This was tested to see if the matching could be performed without a need of an already close alignment, which was needed in the original method (the distance of midpoint to midpoint), if this were not needed, the edge matching could be performed earlier in the process and might eliminate the need for a grid search in some cases. The results of the edge matching in relation to the grid search are discussed in the results section 6.1.2.

Snapping

Snapping the ground floor geometries to the BGT footprint was also considered in an attempt to best match the reference BGT. This was quickly disregarded due to snapping changing the geometry of the source division drawing geometry. Additionally, if the division drawing does not closely resemble the BGT geometry, the snapping process can worsen the results (figure 4.10). This snapping could also warp the interior geometry to invalid or incorrect placement of rooms, propagating throughout the 3D reconstruction. Therefore, it was not further explored.



(a) The alignment prior to snapping (b) Snapping within 0.4 m (c) Snapping on simplified geometries

Figure 4.10.: Comparison of snapping methods

4.1.4. Alignment Cases

While the standard alignment assumes a 1:1 correspondence between the division drawing ground floor geometry and BGT footprint, several other special cases can occur in practice. These cases were manually created and tested to assess the robustness of the alignment process, and used to adjust parameters to improve the performance under these circumstances.

Pillars

According to the BGT specifications by Geonovum (2021), pillars with a size of at least 0.3 x 0.3 m are considered part of the building footprint (figure 4.11). The specifications for division drawings do not mention the inclusion of these pillars. It might be possible for them to be included, even if smaller than the BGT specifications. They might also be removed because they do not provide any information about private or shared spaces.

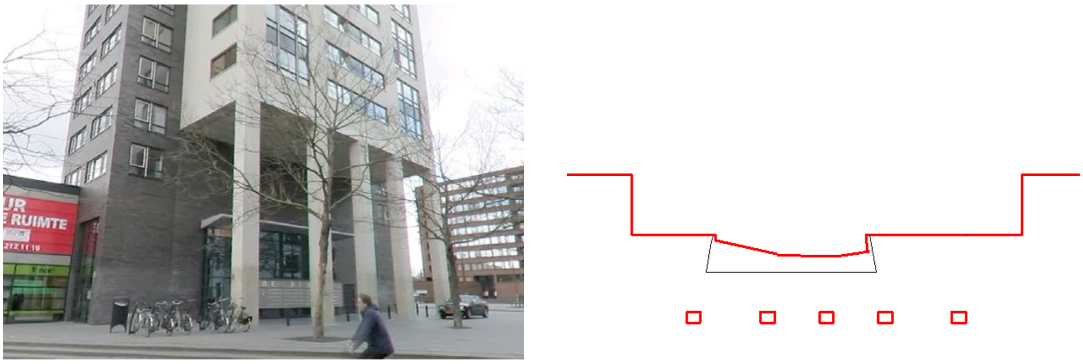


Figure 4.11.: Pillars in the BGT

Another possible source of discrepancy comes from differing interpretations of the ground floor, this is visualized in figure 4.12. The BGT defines the footprint as the area where the building physically touches the ground. The division drawings may represent the ground floor as a usable space closest to the ground. To evaluate this, a case was tested where the BGT includes individual pillars while the division drawing includes the overhanging floor above them.

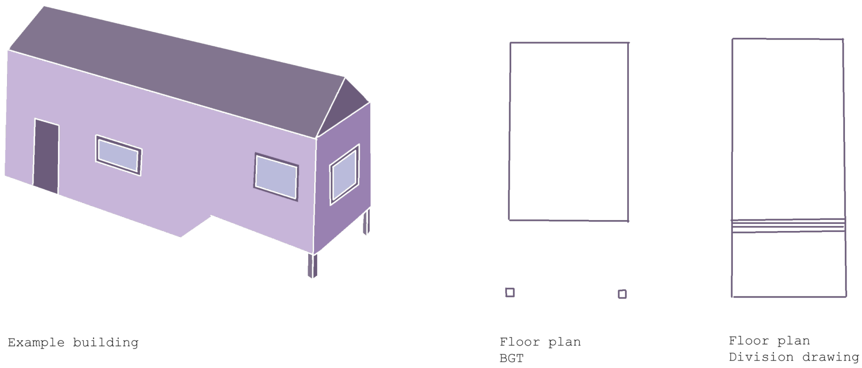


Figure 4.12.: Difference BGT and division drawing footprint

To test alignment performance under these possibilities, three cases were created:

- Both have pillars (n:n).
- One has pillars, the other does not include them at all (1:n).
- One has pillars, the other represents the envelope around the pillars (n:1).

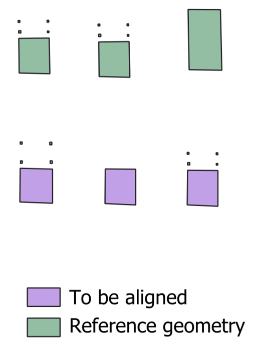


Figure 4.13.: Pillar cases

Multiple Footprints

As noted in section 4.1.1, retrieving the BGT geometry can lead to the selection of multiple footprint candidates. In case they correspond to the correct and same amount of geometries in the division drawing, a similar case as m:m alignment as the pillars happens. The incorrectly corresponding geometry cases that were tackled are:

- One division drawing ground floor aligning to an incorrect amount of retrieved BGT footprints (1:n).
- The division drawing containing more footprints than the BGT due to the difference between "ground floor" and "footprint" (n:1).

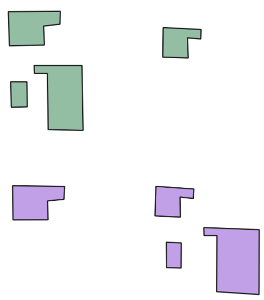


Figure 4.14.: Multiple footprints cases

Partial Matches

Another case is the alignment of partial matching footprints. This could occur for example in the described case of the difference between the division drawing ground floor and the BGT footprint. But also when parts of a building have a separate registration.

- A small piece aligning to a larger footprint.
- A large footprint aligning to a small section.

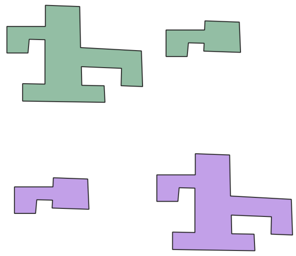


Figure 4.15.: Partial match cases

4.2. 3D Reconstruction

This section describes the process of reconstructing the 3D models, continuing from the georeferenced ground floors. The reconstruction consists of two parts: (1) Aligning the projected footprints of each floor on top of each other in 2D, and (2) estimating the height of each floor, either from data in the division drawing or through an external source.

4.2.1. Floor Alignment

Standard Case

Besides the ground floor, the individual storeys of the apartment building must be properly aligned. They can be represented by their footprints and aligned in 2D. In the case of simple apartments with identical floor plans, this could be achieved by aligning the centroids of each storey. However, often the shape of the building changes across floors, possibly causing the centroids of each floor not to align. Therefore, another method must be used. The alignment using centroids was tested and is shown in figure 4.16. The proposed method for the alignment of the storeys, relies on the presence of consistent geometries across the storeys. Such as: staircases, elevators, and most often, the exterior and load-bearing walls. It should be noted that as described in section 2.1 the geometries in the division drawing do not necessarily coincide with actual walls. Nevertheless, the spaces they represent may still be provide consistent geometric references through the building.

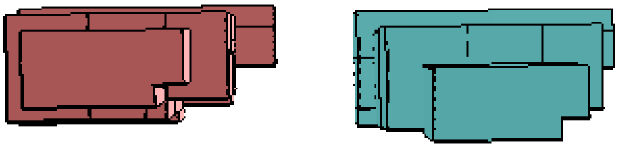


Figure 4.16.: Alignment on centroid (left) and using the proposed method (right)

It is assumed that if these consistent elements are present, each storey will most resemble the storey below it. As such, each storey is fitted to the storey below (figure 4.17). The alignment of basements is handled by aligning them to the storey above instead of below.

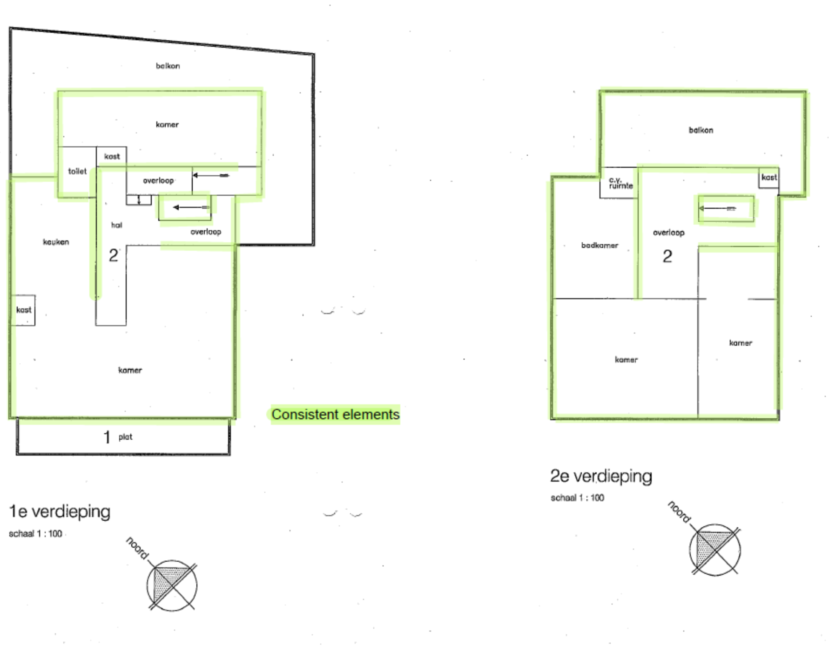


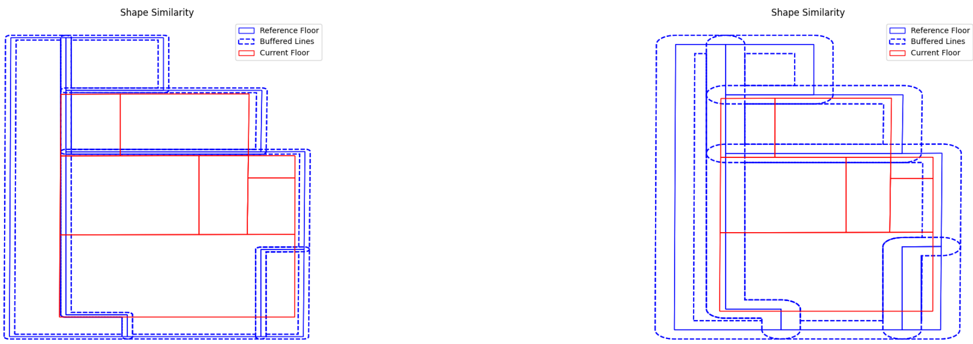
Figure 4.17.: Consistent elements across floors

The 2D shape alignment problem in this case is one that should maximize polyline overlap between floor plan geometries. As such, the area-based overlap is not suitable for this problem. Distance-based metrics such as the Hausdorff and Fréchet distances were also disregarded due to their global nature. In this case, the shape similarity is used, as introduced in section 3.1.1. This metric calculates how much the polylines of one geometry (A) are contained within the buffered (ε) region of another (B). While the original description takes into account a bidirectional fit (A into B and B into A) For the purpose of storey on storey alignment, only the fit of the current storey (A) to the reference storey (B) is necessary.

$$\sigma(A, B) = \frac{\text{length}(A \cap \text{Buffer}(B, \varepsilon))}{\text{length}(A)}$$

Again, a grid search is used to find the optimal translation which in this case maximizes the shape similarity between the corresponding storey geometries. Because it is unknown which walls are consistent, the full interior and exterior geometries are used.

The choice of buffer size around the reference storey depends on two aspects. A smaller buffer generally results in a closer alignment in the reconstructed model. However, when storeys have slight variations in their geometry, caused by drawing inaccuracies (which are more prominent in hand drawn division drawings), a larger buffer is needed to account for this.



(a) Buffer of 0.1 m

(b) Buffer of 0.4 m

Figure 4.18.: Comparison of buffer sizes in shape similarity scoring

Algorithm 4.2: AlignAllstoreys(storeys)

foreach *storey in storeys* **do**
- **if** *storey less than 0* **then**
  - reference_geom ← geometry of storey 0;
- **else**
  - reference_geom ← geometry of storey below;
- **if** *aligned geometry exists for storey below* **then**
  - reference_geom ← aligned geometry from previous alignment;
- current_geom ← geometry of storey;
- aligned_geom ← `GridSearchAlign`(current_geom, reference_geom);

Once the storeys are aligned, snapping can be used to snap the vertices to the reference within a specified threshold. This can however slightly distort the geometries, and is not guaranteed to return valid geometries. The exterior surfaces will be more flush, but whether snapping is desired depends on the use case. For the purpose of the BIM Legal model, it is preferred to maintain more accurate interior geometries.

Exception Handling

There are several special cases that do not conform to the standard alignment method. The first involves storeys that have no similarity to the floor below (or above in the case of a basement). A limitation of the shape similarity metric is that it is purely geometric, meaning that when there is no similarity between a storey and its reference, it is hard to estimate the correct position of the storey. As seen in figure 4.19, for these cases it is assumed the y-position on the drawing is approximately correct, relative to the other storeys. The translation search can then be limited to a very small range in the y direction. This also minimizes the error in the y-axis. In the case the floors are not horizontally aligned on the division drawing document, this assumption does not hold and a larger x and y search range have to be used. This corresponds to the standard search distance as used in the grid search from section 4.1.3.

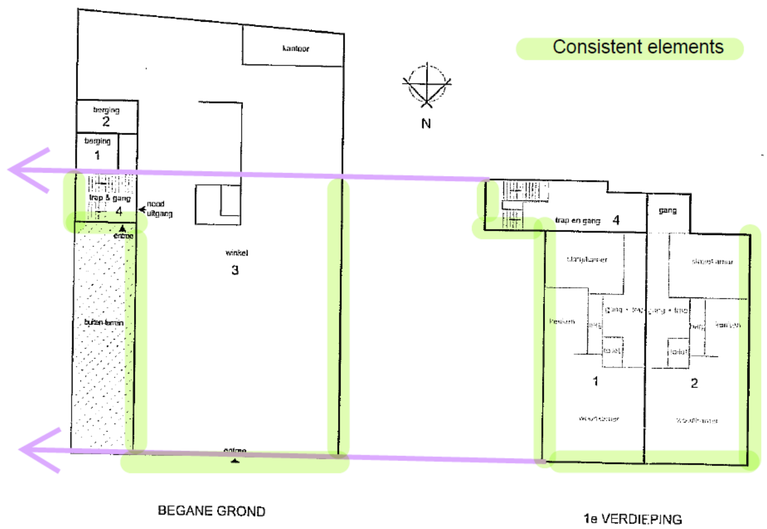


Figure 4.19.: Assuming correct y-position on division drawing

Next, since the storeys are mapped to an index depending on the text corresponding to that storey, any error in the text will propagate through the 3D reconstruction process. For example, if there is no text at all, or if the floor has no number or text indicating which level it is (e.g. "tower"). These instances are not modeled due to their unknown vertical position. Additionally, textual descriptions for more than 10 storeys are not handled. Currently, only textual floor indication of the first ten storeys are mapped (e.g., words like "eerste", meaning "first"). If numbers are used (e.g., 1e), these are always correctly indexed.

4.2.2. Height Estimation

Height From Cross Section

The heights of the storeys can be estimated approximately based on the cross section that is often provided in the division drawings. Since the cross sections are also drawn to scale (Het Kadaster, 2019), they can be used to retrieve room specific information on the height of the storeys, assuming the cross section is made at a representative spot where all storeys are present.

One possible solution to estimate the storey heights would be to calculate the vertical distance between horizontal edges the in the cross section. But, due to split-levels or raised areas what can be considered a "storey" becomes ambiguous, and where the distance between the edges has to be sampled.

As mentioned in section 3.2, for point clouds the heights of the floors are often determined using a histogram of all the points of an indoor scan. These then indicate at peaks where in the z-direction the floors and ceilings, are positioned.

A similar method is proposed for this research, based on the vertices of the cross section. The y-values of all vertices indicate the frequency of a certain height value. These are treated as 1D samples on the y axis, representing the heights of the building. The distribution of these values is analyzed to detect clusters which correspond to storeys.

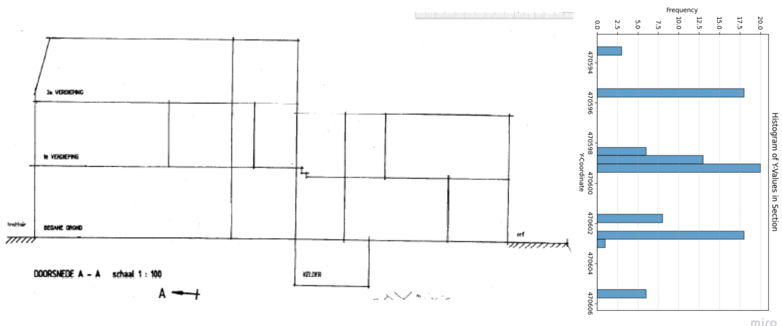


Figure 4.20.: A histogram showing distinct heights (storeys) in the section

To find these clusters, Density-Based Spatial Clustering of Applications with Noise (DBSCAN) (Density-Based Spatial Clustering of Applications with Noise) is applied on the y-values. This is an unsupervised algorithm that allows for the estimation of the amount of floors, without knowing the amount beforehand. The maximum distance between points to be considered a cluster is determined by the epsilon value. By making this smaller, more distinct floors are detected. Note that the detected roof surface is also detected as a storey, this is accounted for by removing the highest detected storey.

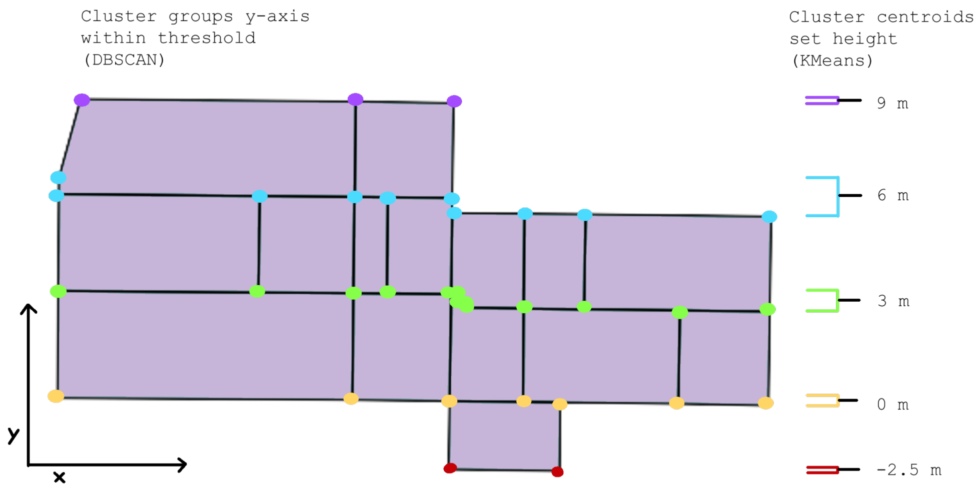


Figure 4.21.: Clustering of y-values to determine the storey heights

The next step is to retrieve the actual storey heights. This is done by applying another unsupervised clustering technique, KMeans clustering. This is initialized with the clusters detected by the DBSCAN. The mean of the detected clusters is returned. These are sorted and assigned to the corresponding floors (figure 4.21).

In theory, this method could be extended to estimate the height per individual space or subfloor. Each space in the cross section could be associated with the height as shown in the cross section. However, this was not further explored in this research for several reasons. First, the cross section does not necessarily show all spaces. The missing spaces would then have no reliable height information and have to be estimated. Secondly, the location of the cross section is unspecified in the vectorized documents, making it difficult to associate spaces in the cross section with spaces in the floor plans. This is however indicated in the division drawings themselves with an arrow on top of the floor plans. If this were vectorized as well, it could potentially be used.

For the scope of this research, in the case where the number of detected storeys does not match the amount of floor plans, an average height is calculated as: the total calculated height divided by the amount of drawn floor plans.

3DBAG Height Estimate

As seen in section **??**, the cross section is not included in about half of the division drawings. For these cases an approximation is made based on an existing 3D model.

The BGT footprints that were retrieved also include the BAG ID, which can be used to retrieve elevation information of the buildings in the 3DBAG dataset. As the final BIM Legal model will be developed in a LoD 1.3 (see section 4.3), the same height estimation as used for these models will be adapted. As described in section 3.3, for the 3DBAG LoD 1.3 models, the building height is estimated to the 70 percentile of the height values from the roof surfaces of the most detailed model, taking into account extreme maximum values on the roof (Peters et al., 2022).

The ground height is also retrieved from the 3DBAG dataset because it provides an accurate reference for the elevation of the buildings base. It is based on the point cloud data within 4 meters around the BAG building (3D geoinformation research group , 2022).
The average storey height is then calculated as:

$$StoreyHeight = \frac{TotalBuildingHeight - GroundFloorHeight}{AmountOfStoreys}$$

The basement height can not be determined from the 3DBAG as it contains only geometry above ground. A preset value of 2.3 m is used, based on common construction standards (Betonhuis, 2020).

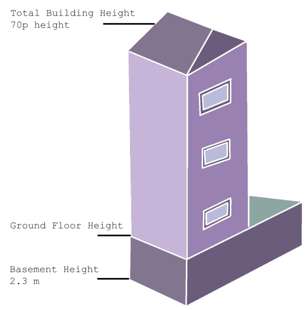


Figure 4.22.: Height determination

In order for the estimation to be more accurate, the method as described by Boeters et al. (2015) in section 3.2 could be used. This method uses the exterior of buildings to estimate the interior vertical storey positions.

Since the division drawings are made for entire apartment buildings, there can be multiple BAG notations inside. For each of these, a different 70 percentile height is retrieved by the 3DBAG API. To account for this, an intersection check is performed on the centroid of each room, to the BAG footprints (figure 4.23), in order to associate each room with the BAG building(s) they belong to. The building heights are therefore BAG specific.

Figure 4.23.: Intersection of each room with BAG geometry

Height Thresholds

In order to account for possible miscalculations, the calculated storey height can be manually verified. Discrepancies may occur when one of the storeys is not accounted for in the division drawing. For instance, when it has a name that is not recognized. In such cases the average calculated height per storey may be higher than expected.

To maintain realistic values, lower and upper thresholds can be applied. If a calculated storey height is less than 2.4 meters, it can be set to 2.4 meters. This corresponds to the minimum building heights standards that were used in the Netherlands before 2012 (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2011). Similarly, if the calculated storey height is higher than 3 meters, it can also be capped.

Depending on user preferences and the characteristics of the input data (e.g., the number and quality of division drawings), estimated storey heights can be handled in several ways. They can either be adjusted automatically based on standardized values. Alternatively, per floor can be chosen to manually set the height to the standardized height, to the user's own given value, or leave it as it was calculated.

4.3. BIM Modeling

The goal of this step is to generate a 3D legal representation of apartment units that follows the BIM Legal standard.

4.3.1. Format Selection

BIM Legal typically assumes an IFC file as input, which is then enriched with legal space information. The resulting 3D models created in accordance to the BIM Legal data model are usually also written in IFC format.

However in this research, the starting point is different. Instead of IFC building models, vectorized division drawings together with other cadastral geospatial data are used to reconstruct the 3D models. Producing an IFC file from this is not straightforward and raised the need to explore alternate formats. An ideal format would meet the following criteria:

- **Ease of generation from geospatial input:** The format should support straightforward construction from geospatial data and support standard georeferencing using coordinate reference systems.
- **3D support:** Since the legal units are represented in 3D volumes, the format should support 3D geometry.
- **Semantic Hierarchy:** It should be possible to encode relationships that reflect the aggregate structures in BIM Legal's data model.
- **Compatibility with standard GIS tools:** The format should be supported by standard GIS software, this allows for easier inspection, validation and analysis.

Table 4.1.: Comparison of GIS file formats as potential BIM Legal format

Format	Hierarchy	GIS Software Support	Georeferencing	Notes
GeoPackage	semantic	✓	✓	
Shapefile	✗	✓	✓	Outdated
CityGML	✓	✓	✓	Verbose structure
IFC	✓	No	Partial	Requires transformation
CityJSON	✓	Plugin	✓	

Several formats were considered. Table 4.1 provides an overview.

From this comparison, CityJSON was selected as the modeling format. This is a compact format that supports georeferenced 3D city objects, in a similar hierarchical structure.

4.3.2. Mapping BIM Legal to CityJSON

The BIM Legal data model introduces hierarchical semantics, such as the distinction between private and shared legal spaces, and the grouping of this spaces into apartments. To encode these semantics, the model was mapped to CityJSON version 2.0.0.

The mapping is visualized in figure 4.24.

Each BIM Legal element is mapped to a corresponding CityJSON element. A *BIMLegalApartmentComplex* is represented as a *CityObjectGroup*, which is the highest class that can encompass other *CityObjects* like buildings. Normally this is used to group *CityObjects* together, but in this case only one apartment complex is added.

The *ApartmentComplex* itself is modeled as a *Building*. These consist of *ApartmentUnits* and possibly *SharedParts*. The class *BIMLegalSpace* exist for the possibility in BIM models that apartments either consist of smaller legal spaces or that the apartment itself is considered the legal space. For this research, when division drawings are used as input, only smaller legal spaces are created. Therefore it was chosen to represent the *ApartmentUnit*, *SharedPart* and *BIMLegalSpace* all as *BuildingUnits*.

The separation of *ApartmentUnits* and *SharedParts* is especially important. This is modeled through the "name" of the *BuildingUnit* which indicates the corresponding BIM Legal entity (figure **??**). Additionally, for *ApartmentUnits* the apartment index is included.

The smallest class is the *BIMLegalSpaceUnit*, being represented by *BuildingRooms*. The objects belonging to this class are the only ones containing any geometry.

```
    "id_3": {
      "type": "BuildingUnit",
      "attributes": {
        "apartmentIndex": "1"
      },
      "children": [
        "id_4", ...
      ],
      "parents": [
        "id_2"
      ]
```

```
    },
    "id_5": {
      "type": "BuildingUnit",
      "attributes": {
        "name": "SharedPart",
      },
      "children": [
        "id_6",...
      ],
      "parents": [
        "id_2"
      ]
    },
```

In addition to the properties defined by BIM Legal, extra attributes are added to the *BuildingRoom* (figure **??**). These attributes include:

- **Space type:** The description that is provided in each space indicating its function.
- **Georeferencing accuracy:** A score indicating the accuracy of the georeferencing process. This is the average of the shape similarity and containment score as presented in section 6.1.4.
- **Apartment index:** Having the apartment index on geometry level as well allows for quick visualization. Having no apartment index indicates a shared part.

A full example of the CityJSON file structure is provided in appendix B.

```
"id_4": {
      "type": "BuildingRoom",
      "attributes": {
        "name": "bedrijfsruimte",
        "extrusion_height": 3.3,
        "function": "bedrijfsruimte",
        "appartmentIndex": 1
                "georef_acc": "86.5",
                "bimLegalSpaceUnitType": "m",
                "level": 0,
      },
```

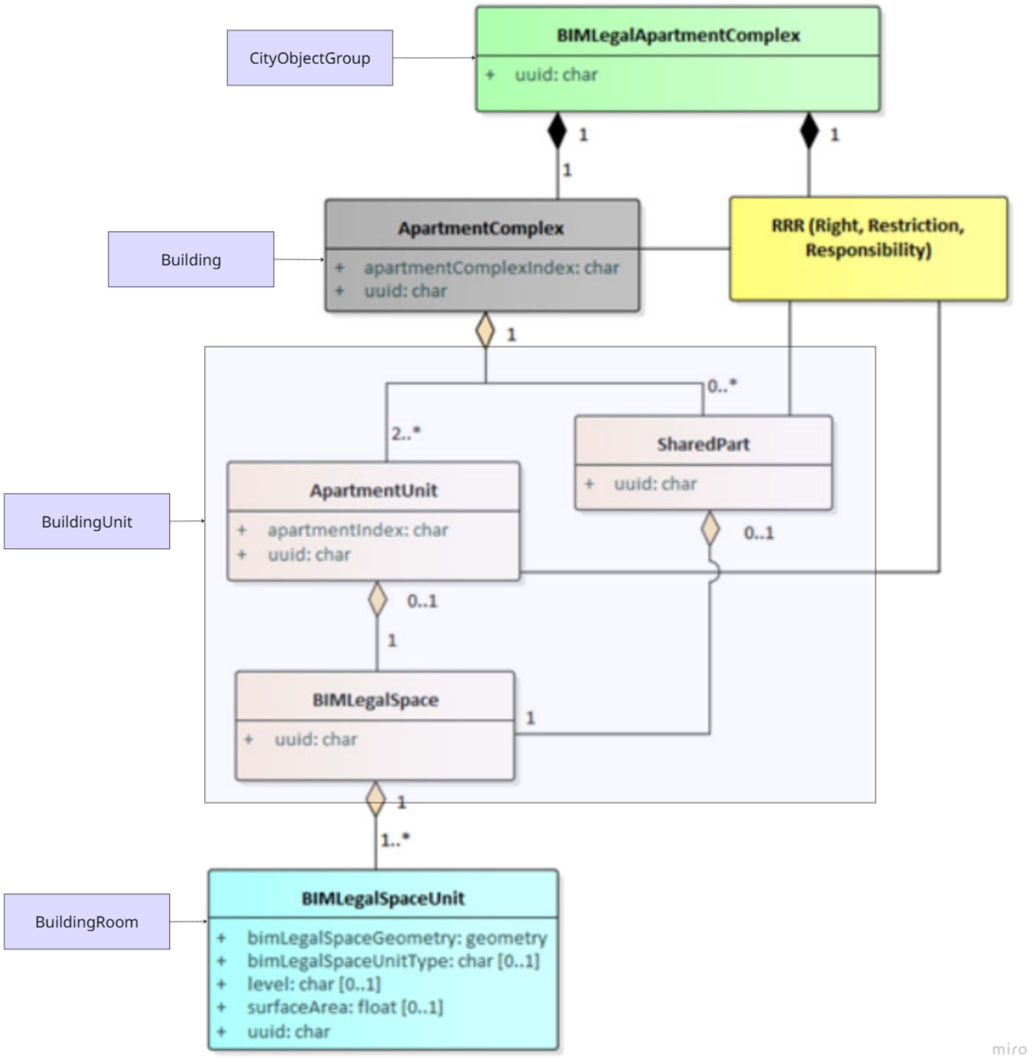


Figure 4.24.: Mapping BIM Legal to CityJSON

4.3.3. Level of Detail Modeling

The BIM Legal data model requires a 3D representation of legal spaces within a building. Specifically, the model must also distinguish between private and shared areas.

In its standard implementation, this modeling approach corresponds to a LoD2+. As seen in figure 3.4, this corresponds to the modeling of storeys, within boundary elements such as walls, roofs, and floors. These themselves are not usable space. As a result, these components are emitted from the 3D representation. Only the actual (legal) spaces are modeled.

However, in this research, the division drawings which are used as source material already depict legal spaces instead of physical elements such as walls. They also lack the detail of wall, roof and floor thickness. It is therefore not logical to reconstruct LoD2+ models from this input.

Instead a simplified version is used that corresponds to LoD1+. In this approach, the legal spaces are represented as extruded volumes based on their floor plans and estimated heights. For the purpose of the legal visualization, just like the LoD2+ BIM Legal, the separate legal spaces are also modeled.

It is also important to note that the legal boundaries of the exterior spaces are not well-defined. While interior spaces are clearly enclosed by floors and roofs, the exterior spaces could extend vertically without limit. Nevertheless, for consistency, these exterior volumes have been assigned the same height as the calculated extrusion height used for the interior volumes on the corresponding storey. No distinction is made between interior and exterior spaces in the modeling process, both are represented as 3D volumes.

4.3.4. Valid CityJSON modeling

To construct the 3D geometry of the legal spaces, each space was modeled as a simple extruded solid, as per LoD1+ requirements. The modeling process begins with the vectorized 2D footprints extracted from the division drawings. Each storey was assigned a height based on the index of the storey, and the extrusion height as calculated in section 4.2.2. This creates a 2.5D representation of the flat storey geometries vertically stacked.

Then the surfaces that make up the 3D model can be created. Each surface is created counter-clock wise in order to create outward pointing normals. This is required for visualization as the normal orientation determines how surfaces are interpreted by 3D visualization tools.

The surfaces are modeled for each space individually. Firstly, the base geometry is stored, which is copied to the extrusion height to create the top geometry. Then, again in counter-clockwise order, the wall surfaces are created by looping around the base and top geometry. A MultiSurface geometry was used instead of a Solid to allow adjacent spaces to share surfaces without duplicating geometry.

Additionally, the floating point coordinates were scaled to be represented by integers. Geometric validity of the output CityJSON files was evaluated using *val3dity* (Ledoux, 2019) , (Ledoux, 2013), which checks for common 3D modeling issues such as self-intersections and duplicate vertices. Schema compliance to CityJSON 2.0 was verified using *cjval* (Ledoux, 2023).

5. Tools and Datasets

The specific tools and datasets used in this research are described in section 5.1 and 5.2, respectively. Additional background is given to the following datasets: The cadastral building datasets (5.2.1) and links between datasets (5.2.2)

5.1. Tools

The workflow developed in this research, from georeferencing and 3D reconstruction to visualization, was implemented in Python. The following libraries were most vital:

- *Geopandas (Jordahl et al., 2020):* This library expands on the *pandas* library to support geospatial operations. It was used to read, manipulate and write spatial data in dataframes.
- *Shapely (Gillies and contributors, 2007–2023):* Together with *geopandas*, this library supported the spatial operations, like buffering, intersections and unions.
- *Matplotlib (Hunter, 2007):* This library was utilized for visualizing the spatial data and creating plots.

In addition to Python, the open-source GIS platform *QGIS* was used to visualize intermediate shapefile results, as well as 3D models. Created CityJSON files could be loaded into QGIS through the plugin CityJSON Loader (3D geoinformation group (TU Delft), 2025).

Finally in addition to *QGIS*, *Ninja* (Vitalis, 2025) was used to validate and visualize the output of the 3D reconstruction. This was especially useful for verifying the structure of the created BIM Legal models.

The developed code for this research is openly available at: `https://github.com/lottedeniet/Thesis_reconstructing_3D_BIM_Legal_models`

5.2. Datasets

This research uses several datasets that support the complete workflow to 3D BIM Legal models. Each dataset contributes to a specific phase in the process. When georeferencing the ground floor of the division drawing, 2D cadastral datasets are needed to align the division drawings. For the 3D reconstruction, the geometry of the floor plans in the division drawings serve as main reference for aligning the storeys and the cross section (where available), for estimating the storey height. The 3DBAG dataset provides an additional reference for estimating the height.

An overview of all datasets used in this research is provided in table 5.1.

Table 5.1.: Overview of datasets

Dataset	Format	Source	Role in Workflow	Open Dataset?
Division Drawings (Scanned)	PDF	Kadaster	Original reference documents	Open (on request)
Division Drawings (Vectorized)	JSON	Kadaster	Primary input that will be georeferenced and reconstructed in 3D	Not Open
BGT	JSON	PDOK (OGC API)	Georeference alignment reference	Open
BAG	JSON	PDOK (OGC API)	Building attributes and linking to 3D	Open
BRK	Shapefile/ JSON	Kadaster	Georeference alignment reference	Open
3DBAG	JSON	TUDelft3D and 3DGI	Height reference	Open

5.2.1. Kadastral Building Datasets

In order to align the division drawings and reconstruct the legal 3D models, a combination of Dutch cadastral datasets is required. As shown in table 5.1, three primary sources are usedk: the BRK, BGT, and BAG.

- **BRK** (Basisregistratie Kadaster): This registry provides cadastral parcels and legal property boundaries. Each parcel has a unique identifier that is used for linking the division drawings to property registrations.

- **BGT**: The *Basisregistratie Grootschalige Topografie* represents the physical environment. The building geometries in the BGT refer to the footprints of the buildings.

- **BAG**: The *Basisregistratie Adressen en Gebouwen* contains information on all addresses and buildings in the Netherlands, such as construction year, area, purpose, and location. Its building geometries are representing the projected outerline as seen from a top-down view.

For the 3D reconstruction step, an additional dataset is used: the **3DBAG**. This is an open 3D dataset derived from the BAG and the AHN (Actueel Hoogtebestand Nederland). The 3DBAG building models for most of the Netherlands, in various LoDs (Peters et al., 2022).

In table 5.2 an overview of the used attributes from the cadastral data sets is given.

Table 5.2.: Cadastral attributes

Attribute	Description	Type	Source	Used in
bag_id	Unique identifier	String	BAG/BGT	Dataset linking
oorspronkelijk-bouwjaar	Year of construction	Integer	BAG	Height and wall thickness determining
Status	Status of the object lifecycle	String	BAG	Check if building demolished
geometry	2D footprint	(Multi)-Polygon	BGT	Georeferencing reference
b3_h_dak_70p	70th percentile roof heights	Float	3DBAG	Storey height estimate
b3_h_maaiveld	Ground height of the building	Float	3DBAG	Setting ground height of 3D building

5.2.2. Dataset Linkages

Several linkages were required to combine datasets. Table 5.3 shows these connections.

Table 5.3.: Overview of dataset linkages

Source Dataset	Target Dataset	Key Attribute	Link Method
Division Drawing JSON	Kadastrale Kaart	Parcel ID (perceel_id)	String match
Kadastrale Kaart	BGT	Building geometry	Spatial intersection
BGT	BAG	BAG ID (bag_id)	String match
BAG	3DBAG	BAG ID (bag_id)	String match

6. Results

This chapter presents the results obtained from the implementation and performed experiments as described in chapter 4. The results are structured according to the methodology. The chapter begins with section 6.1, an evaluation of the georeferencing performance, including the experiments performed on initialization and optimization. Then the 3D reconstruction is described in section 6.2, this consists of the floor alignment and height estimation. Then the results of the BIM Legal modeling process are summarized in section 6.3. Each component has been analyzed both quantitatively and qualitatively, and its limitations are described. Where applicable, comparisons are made between different approaches and parameters. Finally, an overview is given of the final pipeline in section 6.4.

6.1. Georeferencing Evaluation

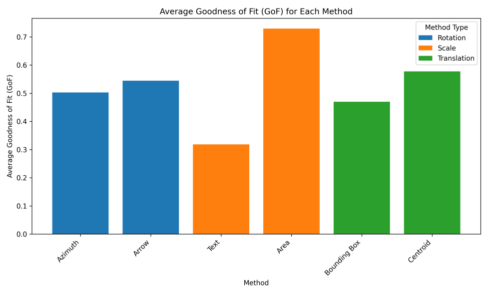
This section assesses the performance of different georeferencing approaches used to align the division drawings with their corresponding BGT reference geometries. It is structured in the following stages: Initialization, exhaustive search metrics selection, edge matching, a general performance assessment, and the limitations. The aim is to find robust methods that could be used to align a diverse and large amount of division drawings.

6.1.1. Comparison of Georeferencing Initialization Methods

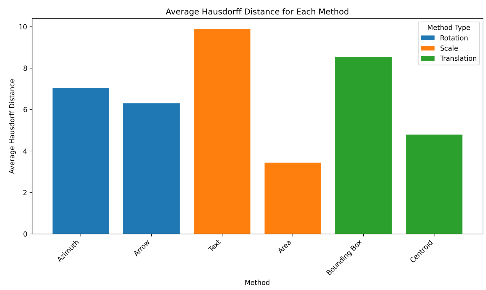
Two methods of initialization were tested per transformation. The resulting geometries after initializing are compared to their BGT counterpart using the GoF and Hausdorff metrics. These metrics do not necessarily indicate a “good” fit, but can be used to compare the performance across methods. These scores in figure 6.1 were calculated by running each combination of transformation methods and then averaging the scores per metric. The performance per transformation is described in the following sections, finally an overview of the alignment using the best initialization methods is shown in table 6.3.

Rotation

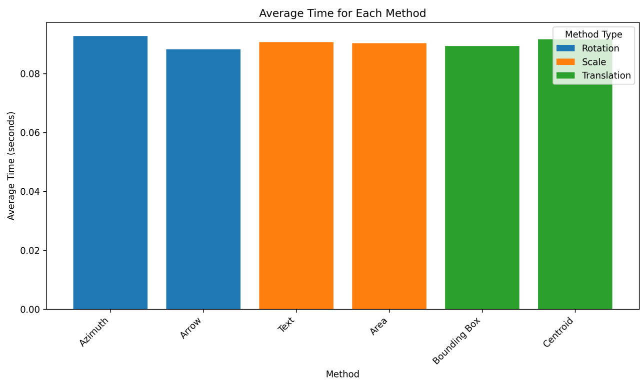
Both rotation methods perform very similarly, with the method utilizing the north arrow performing slightly better. However, both methods also have drawbacks. First of all, the north arrow would have to be detected during the vectorization of the division drawing using image detection algorithms, in order to retrieve the rotation angle of the floor plans. The advantage of this method is that it is source dependent. Utilizing the azimuth is geometry dependent and can give an error of 180 degrees. This is due to the middle line in the calculation not specifying direction. This can be seen in figure 6.2. As a result, the rotation search range in the later optimization has to be enlarged to the full range of angles. The choice was



(a) Average Goodness of Fit



(b) Average Hausdorff distance



(c) Average runtime

Figure 6.1.: Overview of the initialization transformation performance

therefore made to only initialize the rotation if the angles are given, which also significantly reduces the rotation angle search range and computation time.

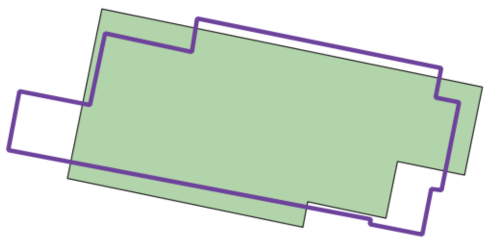


Figure 6.2.: Azimuth initialization result

Scale

For the initial scale estimate, using the polygon area outperforms relying on the scale text from the division drawings. While using the text is significantly faster when it is directly linked to the corresponding floor, this is only true for about half of the cases. Often in practice, most architectural floor plans use the same scale, with the site plan being the main exception. Therefore, when the scale text is not directly linked, the most common occurring scale ratio (the mode) in the whole vectorized file is used. The search through the whole file causes the computation time to be similar on average. The GoF metric is biased to using the area, because both rely on the maximizing of area overlap. However, since the area method also achieves a better average Hausdorff distance, this method is preferred for the final workflow. Whenever the scale text is linked directly to the floor, it is still used as an additional sanity check for the calculated scale.

Translation

Overlaying the centroids performs better than using the bounding box. In the case of 1:n, or n:1 alignments, this method would also provide an overall closer estimate than the bounding box alignment. For these reasons, the centroid alignment was chosen for the final implementation.

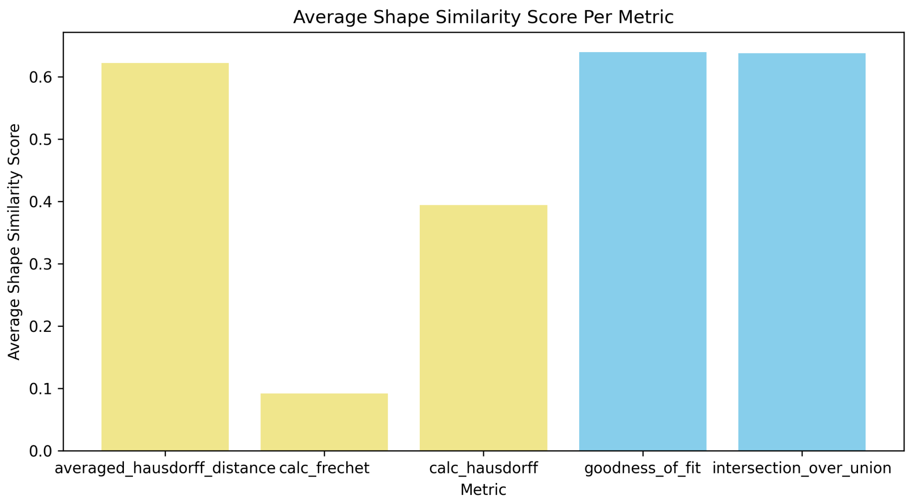
Legend: Green = Division drawing ground floor outline, Purple outline = BGT footprint geometry

Figure 6.3.: Initial alignment results using azimuth rotation, area scaling, and centroid translation

As can be seen in figure 6.3, the biggest source of error is the rotation. Additionally, some resulting alignments are already very close (555/556 and 2359). These cases can skip the refinement (6.1.2), this is further elaborated on in section 6.4.

6.1.2. Comparison of Grid Search Metrics

The next step is the exhaustive closer alignment. Different metrics were used to evaluate which best align the division drawing geometries to the BGT geometries. They have been compared using the shape similarity score, with a buffer of 0.2 m. In addition to this, they have been visually compared, especially to see if the rotation has been performed adequately. For (near) symmetric buildings, the rotation could be off, whilst having a high shape similarity score.



Legend: Yellow = Boundary based metrics, Blue = Area based metrics

Figure 6.4.: Average Shape Similarity Score per Grid Search Metric

As seen in figure 6.4, the two area based methods perform very similar. With the Goodness of Fit metric performing slightly better. The two metrics are also very similar. The GoF favors the division drawing, the IoU treats both shapes equally. Meaning that if the footprint in the division drawing is small, and the reference is large, the GoF score will be higher than the IoU.

As for the boundary methods, the Fréchet distance does not perform well at all. It is structurally sensitive, meaning that in the case of zigzags/more detail in the division drawing, the distance becomes very large, even though the overall shape aligns well. The normal Hausdorff distance performs slightly worse than the average Hausdorff. However, the average Hausdorff distance likely has a high average shape similarity score because it minimizes the total distance between the curves, making the shape similarity consistently high. However by visually comparing the results in figure 6.5, the normal Hausdorff distance performs better in almost symmetric cases.

Overall, the normal Hausdorff distance and the Goodness of Fit were chosen as metrics for further evaluation.

Figure 6.5.: Hausdorff (left) vs Averaged Hausdorff (right)

Using either solely a boundary or solely an area metric resulted in some incorrect alignments. Therefore it was also tested to use a weighted score of both.

Metric Weights

The value for this weight was explored by combining different metrics with different weight values. As can be seen in table 6.1, not all possibilities were tried. The combinations that were tested have been given an indicator of the overall alignment, this was manually verified.

- Good: all approximately correct, no large rotational errors
- Okay: maximum of one building with a large rotational error, some translation or scaling errors.
- Poor: multiple errors in all transformations.

Metric Combination	$\alpha = 0.0$	0.2	0.5	0.8	1.0
Hausdorff and GoF, no translation	Good	Okay	–	–	Poor
Hausdorff and GoF, no translation or initialization	Okay	Good	Good	Okay	Okay
Hausdorff and GoF	–	Good	Good	Good	–
Average Hausdorff and GoF	Good	Good	Okay	Poor	–
Hausdorff and IoU	Good	Okay	Okay	Okay	Okay
Average Hausdorff and IoU	Okay	Okay	Poor	–	–
Fréchet and IoU	Poor	–	Okay	–	–

Table 6.1.: Visual alignment quality for different metric combinations and α weights.

From these experiments it was concluded that a weight favoring the area metric (a higher value) overall performs worse. The ideal value seems to lie around 0.2. The alignment also performs better when the transformations are initialized, and when the translation is also searched, in addition to the rotation and scale.

Alignment Cases

The different cases as described in section 4.1.4 were also tested with a variety of parameters in order to find a solution that would find the best alignment for all cases.

The experiments used the chosen metrics: Goodness of Fit and the Hausdorff distance.

Interestingly, half of the cases performed better using the GoF, and the other half using the Hausdorff distance. Depending on the type of geometry. These results are presented in table 6.2.

Division Drawing Geometry	BGT Geometry	Optimal Weight α
MultiPolygon	MultiPolygon	0.25 / 0.75
MultiPolygon	SinglePolygon	0.25
SinglePolygon	MultiPolygon	0.75

Table 6.2.: Optimal metric weight α per geometry combination

(a) MultiPolygon onto MultiPolygon

(b) MultiPolygon onto SinglePolygon

(c) SinglePolygon onto MultiPolygon

Figure 6.6.: Alignment Single and MultiPolygons

Using a weight of 0.4 also worked for all cases, but it was much more sensitive. For example, using 0.41 already showed different results. Values around 0.25 and 0.75 were more tolerable. That is why it was chosen to dynamically adjust the weight according to the kinds of input geometry.

The described 1:1 partial match cases also worked once increasing the translation search range dynamically (figure 6.7).

6.1.3. Edge Matching

Edge matching was also tested using the method described in section 4.1.3. Initial results showed very few successful edge matches due to the division drawing geometry containing lots of extra vertices. After simplifying, more matches were found. However, the improvements in alignment are minor.

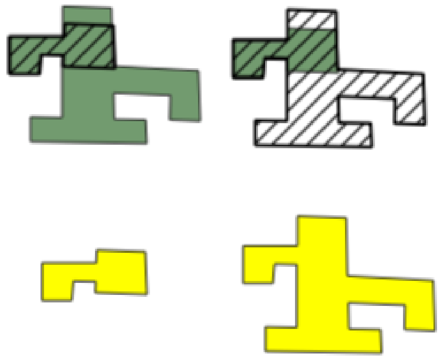


Figure 6.7.: Partial match result (weight 0.25)

Legend: Yellow = Test division drawing geometry, Green = Test BGT geometry, Hashed = Alignment result

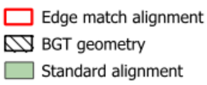
The method heavily depends on spatial proximity of edges, which is incorporated in the midpoint distance feature. As a result, edge matching only performs well when the initial alignment is already close.

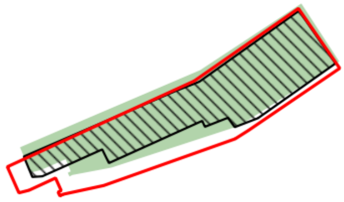
Figure 6.8 shows some experimental results. Standard alignment refers to the exhaustive alignment as described previously.

It should be noted that for some buildings like figure 6.8a and 6.8b it is also ambiguous what the "correct" transformation is, when the BGT and division drawing differ a lot. The original alignment is still preferable, as the mismatch between the BGT and the division drawing here stems from an incorrect vectorization as discussed in section 6.1.4, figure 6.11b.

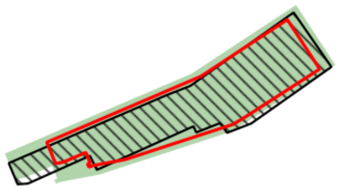
The alternate version using only slope, edge length and vertex angles was tested, without considering the distance. This version did resulted in many incorrect matches, as seen in figure 6.9.

Overall, edge matching did not yield positive results. It relies too much on a good initial alignment with minor improvements and was therefore not used in the final pipeline. This method might provide a less exhaustive alternative to the alignment if different or more features are used.

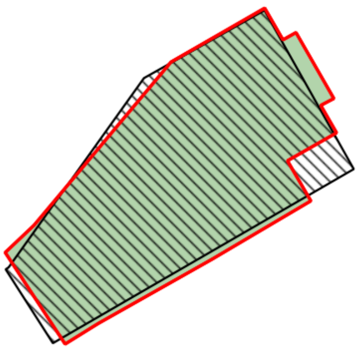




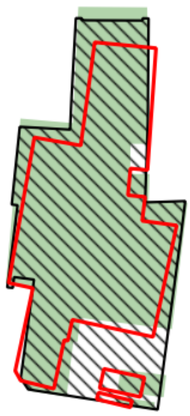
(a) Potential improvement (distance = 0.5m, angle = 3°, length = 0.2m, minimum of 2 matches)



(b) Potential improvement (distance = 0.5m, angle = 3°, length = 0.2m)



(c) No matches found for all tests



(d) Worse results (distance = 1m, angle = 5°, length = 0.5m)

Figure 6.8.: Edge matching results under different parameters

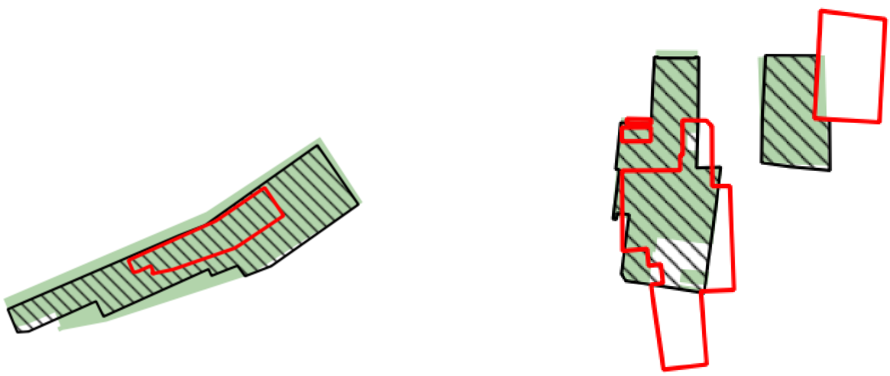


Figure 6.9.: Incorrect matches (Slope = 5°, angle = 5°, length = 0.5m)

6.1.4. Georeferencing Performance Assessment

Table 6.3 provides an overview of the georeferencing results per building. The results reflect the alignment of division drawing footprints to the BGT geometries by optimizing translation, rotation, and scale. They were optimized using a combination of the Hausdorff distance and Goodness of Fit metrics, weighted according to geometry type.

For each building, the containment and shape similarity scores are given, and an overall assessment of the total performance. In the figures, the alignment of the ground floor of the division drawing to the outline of the BGT geometry is shown.

The shape similarity score again shows the similarity between the outlines of the two geometries, using a buffer of 40 cm on either side (figure 6.10). The BGT mandates an accuracy of 20 cm, but given the noisy input data (possibly hand-drawn), an accuracy of 40 cm is used here.

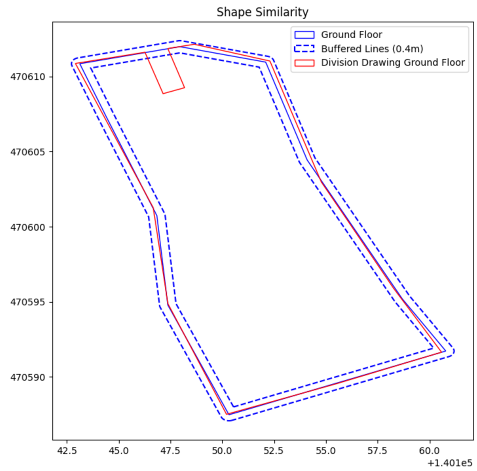


Figure 6.10.: Shape similarity comparison division drawing and BGT

The containment score shows the area of the division drawing ground floor that is contained within the BGT. Given that the BGT is the footprint of the building, the division drawing ground floor should in theory be contained within or align exactly. A high containment score does not necessarily imply an accurate match, it could give a high score for buildings with too small a scale, being contained by the BGT. But together with the similarity score it does indicate the overall alignment. A low shape similarity score also does not necessarily indicate a bad match, given that the notarial drawings can have a different shape than the division drawing; they can however give an indication of why the containment score is low. If both scores are low, it is probable that the georeferencing is faulty.

Overall, the georeferencing performance was acceptable. The average containment was 89.7%. Based on visual inspection, all buildings are translated, scaled and rotated approximately as expected. Overall the accuracy very much depends on the similarity between the division drawing and the BGT.

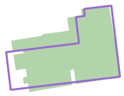
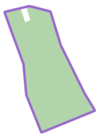
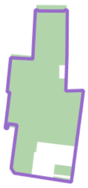
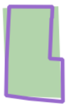
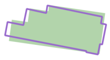
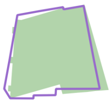
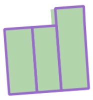
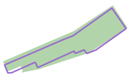
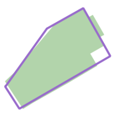
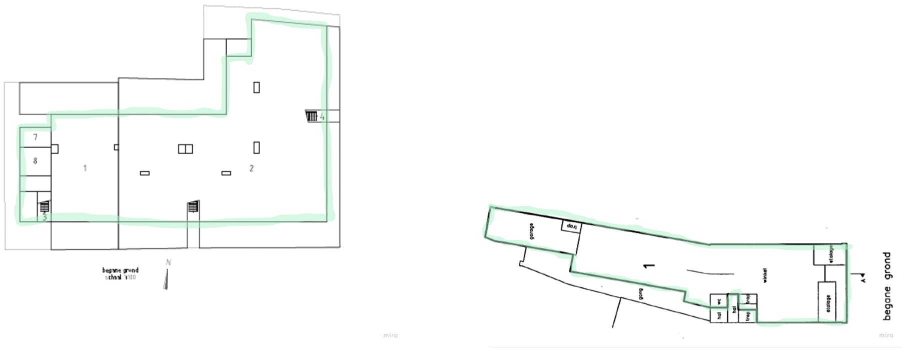
ID	Image Alignment	Shape Similarity	Containment	Issue (<85%)
9252		30.9%	80.3%	Both
555/556		91.8%	98.1%	-
1878/1879		54.2%	94.4%	Drawing
1882		38.0%	86.3%	Drawing
2359		90.6%	97.8%	-
2643		64.1%	86.1%	Drawing
2848		30.4%	91.2%	Drawing
3211		94.8%	96.7%	-
3723		20.7%	73.4%	Both
4216		85.5%	92.9%	-
Mean		60.1%	89.7%	
Min		20.7%	73.4%	
Max		94.8%	98.1%	
Std Dev		27.6	7.7	
<85%		6/10	2/10	

Table 6.3.: Overview Georeferencing Results

Buildings 555 and 3211 had the best alignment, these are also very similar in shape, and so they can align almost perfectly. Several buildings displayed a lower shape similarity score with a high containment score, these are cases where the division drawing geometry shows bigger differences, but were still georeferenced appropriately.

The two worst cases have especially differing input, this signals that there might be an error.



(a) 9252 (b) 3723

Figure 6.11.: Line thickness error

In the case of 9252 and 3723: The private gardens are included in the geometry because they are private property. However, in the BGT only the footprint of the building is considered, in this case the difference between the geometries was quite big.(figure 6.11a and 6.11b). The resulting translation is slightly off due to this.

Averaging the results based on whether the outside area was included or not (table 2.1) shows that this has a big influence on the georeferencing result.

Outside space included: 1882, 2643, 3723 and 9252. Have a mean of: 81.5%. Outside space removed or non existing: 555, 1878/1879, 2359, 2848, 3211, 4216. Have a mean of: 95.2%.

A lower containment score makes sense for the buildings with an outside space, as this often lies outside the BGT barrier. Sometimes resulting in a visual misalignment as well.

Despite these differences, all of the sampled buildings were georeferenced approximately correctly, as far as possible. The quality of the division drawing, and coincidentally the quality of the vectorization of this division drawing, are important factors. They are not 1:1 with the BGT and cannot be seen as a ground truth, the accuracy of the model heavily relies on this.

6.1.5. Limitations and Recommendations

There are some limitations to used methods and metrics as resulted from the experiments.

Limitations

- **Symmetric buildings:** The grid search is sensitive to symmetry in buildings, as all possible rotational fittings are tested.
- **Discrete step size limitations:** The alignment is limited by the discrete scale, rotation and translation step sizes in the grid search.
- **BGT reference:** The BGT does not always reflect the geometry that is included in the division drawing, mainly due to outside spaces which are sometimes drawn.

Recommendations

- **North arrow vectorization:** If the angle of the north arrow is detected in the vectorization step, it can be used to initialize the rotation. This allows the grid search rotation range to be limited around the initial value, reducing computation time and possible geometric errors, including those from symmetric buildings.
- **Scale text vectorization:** Scaling would also benefit from proper scale text vectorization and linking to the floor geometries.
- **Machine learning optimization:** Instead of using the computationally expensive grid search, a gradient based optimization algorithm could be used. This would also remove the need for discrete step sizes.
- **BAG as fallback:** The BAG could be used as fallback when the BGT geometries are too different from the footprint in the division drawing.

6.2. 3D Reconstruction

This section presents the results of the 3D reconstruction process, which builds upon the alignment of the ground floor of the division drawing to the BGT. Firstly the 2D floor plans have been aligned to the floor below. Then also the height estimation is evaluated and compared to known 3D information. Both results have been assessed visually and quantitatively, and lastly the limitations and recommendations are discussed.

6.2.1. Floor Alignment Results

In order for the 3D models to be created, the separate storeys have also been aligned on top of each other. In this section, the method as described in 4.2.1 is evaluated.

Figure 6.12 shows the alignment results using a buffer size of 0.2 meters. The results are visualized through a manual classification of correct alignment to the storey below. Green indicates a successful alignment, and purple represents cases where the alignment was visually too far off, beyond the buffer size.

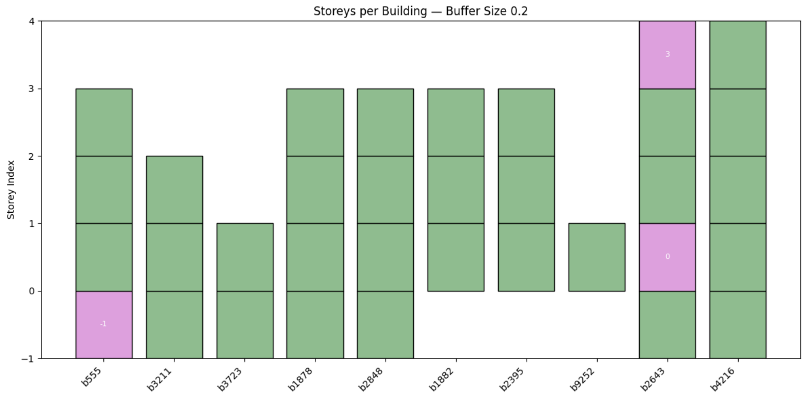
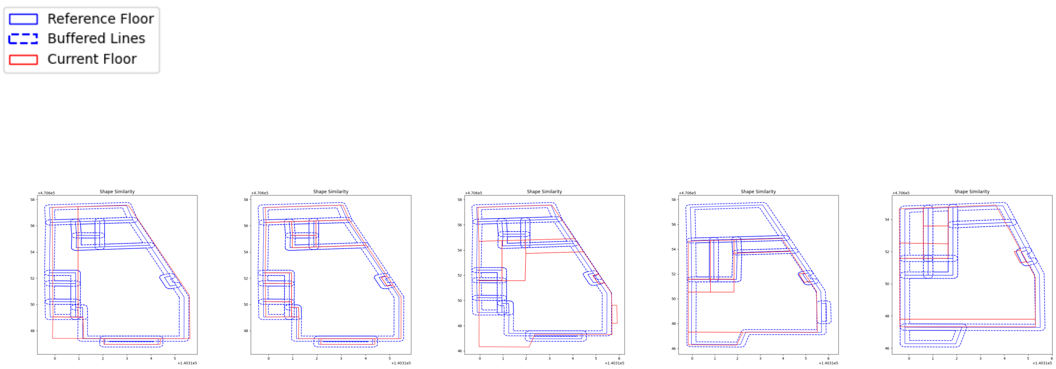


Figure 6.12.: Correct (green) or incorrect (purple) alignment to floor below

While the shape similarity score is computed during the alignment process. It does not indicate the success of an alignment. This is due to storeys not being geometric copies of one another. For example, if storeys were copies, the best shape similarity score would be 1, indicating a perfect fit. But, when the storeys are less similar, for example, the storey misses a balcony, the best possible score could be 0.8. Therefore, a low similarity score does not necessarily indicate a misalignment. Instead, the alignment was manually checked.

Figure 6.13 shows an example of storeys that align well.



(a) Basement (b) Ground Floor (c) First Floor (d) Second Floor (e) Third Floor

Figure 6.13.: Alignment building floors (4216)

It was also tested whether it would be be possible to rely on the exterior geometry alone. However, the results are significantly worse. As illustrated in Figure 6.14a, aligning only the exterior walls can cause the wrong exterior edges to align simply because there is larger buffer overlap for similar, but not corresponding, long straight sections, while in reality they should align more on the side that has ridges. Having the interior (load-bearing) walls can provide more reference so that the correct reoccurring structures are aligned (figure 6.14b). This is especially apparent in basements, where exterior most often does not correspond to the ground floor outer walls.

(a) Align on exterior only (b) Align on exterior and interior

Figure 6.14.: Comparison of used geometry in alignment

Exception Handling

The exception handling as described in section 4.2.1 was considered due to the misalignment of one case. Figure 6.15 and 6.16 shows the improved results when the y-axis translation is limited to a maximum of 0.5 meters.

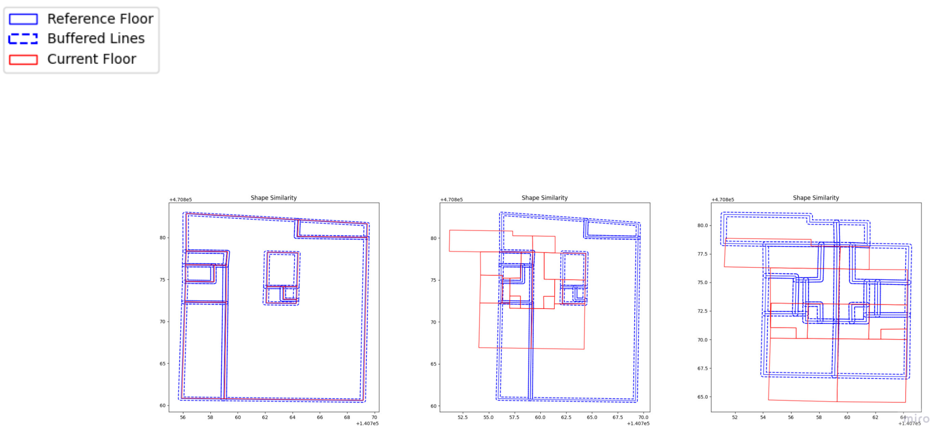


Figure 6.15.: Non aligning storeys using the same maximum search distance for x and y-axis

Despite these changes, there are limitations to this method whenever storeys are very dissimilar. For building 555, the basement geometry is small and dissimilar to the ground floor, which still causes the alignment to fail. However, on the y-axis, this is now limited to an error of 0.5 m (figure 6.17).

Buffer Influence

Figure 6.19a and 6.19a show the alignment results when using an increased buffer size of 0.4 meters.

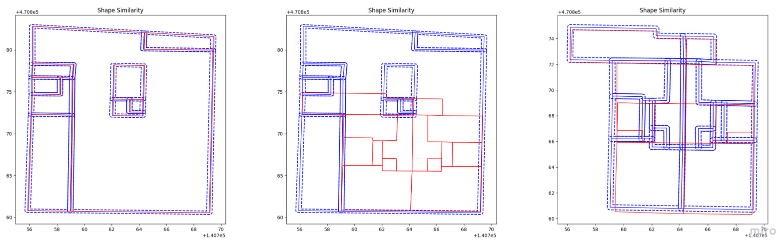


Figure 6.16.: Aligning storeys using a maximum y-axis search distance of 0.5m

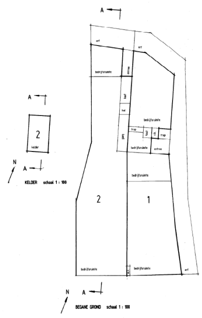


Figure 6.17.: Non similar "kelder" (basement) geometry

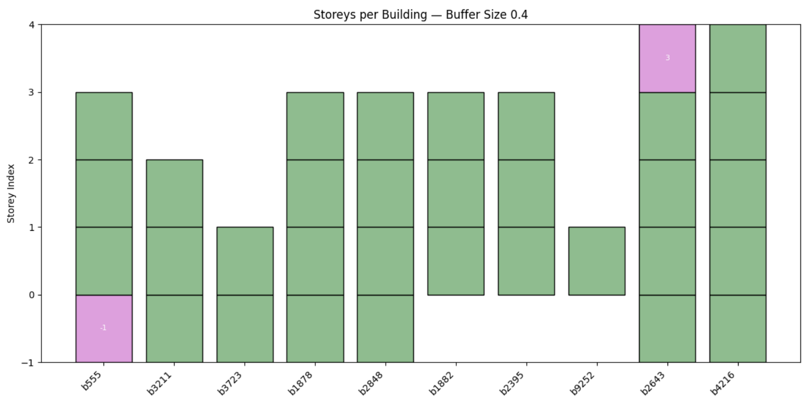
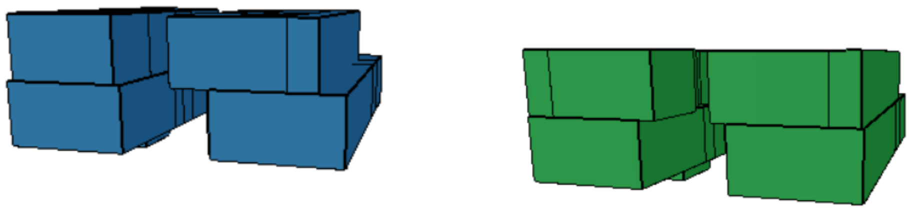


Figure 6.18.: Buffer of 0.4 m.



(a) Buffer of 0.4 m, large horizontal shift (b) Buffer of 0.2 m

Figure 6.19.: Comparison between buffer sizes in 3D

As mentioned in section 4.2.1, increasing the buffer size causes less error because it is less precise. But the resulting 3D models have significant horizontal shifts. Therefore, a buffer size of 0.2 meters was chosen as it balances accuracy, flushness of the model and robustness against the noise of the vectorized input data.

The building shown in figure 6.19 is a special case. The center block of the building has been labeled as "demolished" in the BAG dataset, and as such does not return a height value. However, according to the BGT dataset, a new geometry has been registered in this location, which is the reference geometry that also corresponds to the division drawing. This results in a misalignment between the BAG and BGT, and in this case the removal of the rooms of the center block.

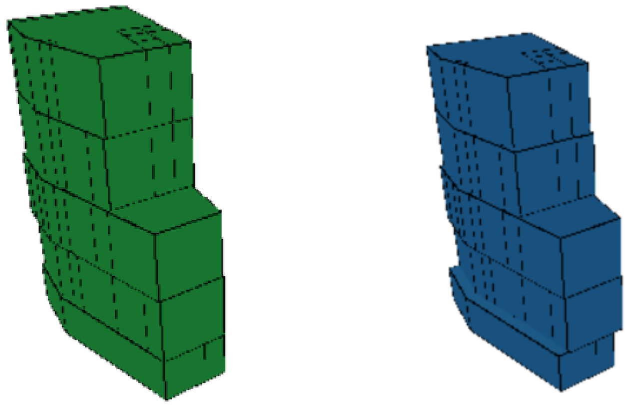
Error Propagation

The storey alignment can cause severe error propagation upwards through the building. Misalignment at a lower level (e.g. ground to first floor) directly affects all further alignments. In the case of figure 6.20b, this is a slight misalignment due to the large buffer. With actual wrong placement such as figure 6.15, the error would be much larger.

Influence of Snapping

There are several sources of distortion in the input division drawings. First of all, hand-drawn drawings inherently have small distortions. In addition to this, the grid search is limited by its buffer and translation step size. These instances cause the model to be limited in its alignment. (figure 6.21a).

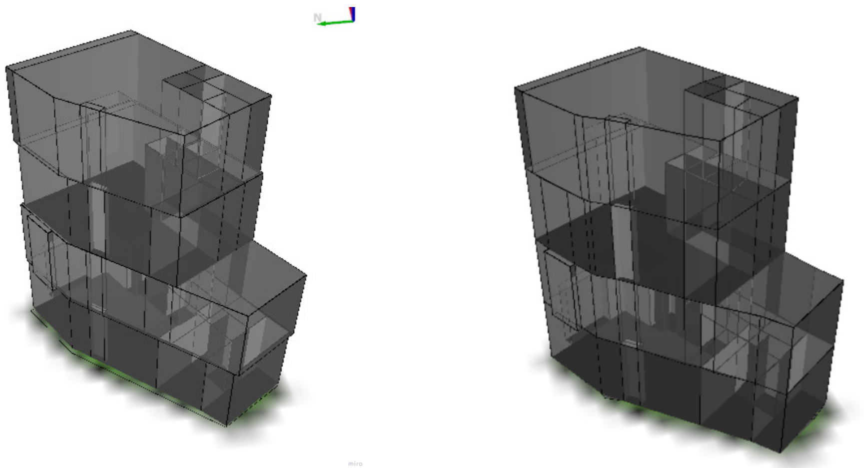
To reduce these effects, especially for visualization as in figure 6.21b, the effects of snapping were tested. The storeys can be snapped to one another using shapely's snap. This can however impact the accuracy of especially the interior. As seen in figure 6.22, some interior walls are now positioned diagonally. It is also not guaranteed to return valid polygons due to possible overlapping polygons or self-intersections.



(a) No error propagation (buffer size = 0.2 m)

(b) Error propagation from the ground floor up (buffer size = 0.4 m)

Figure 6.20.: Comparison of 3D model results with and without error propagation



(a) Created 3D model after aligning the storeys

(b) With snapping (tolerance 0.2m)

Figure 6.21.: Comparison of 3D storey alignment results with and without snapping

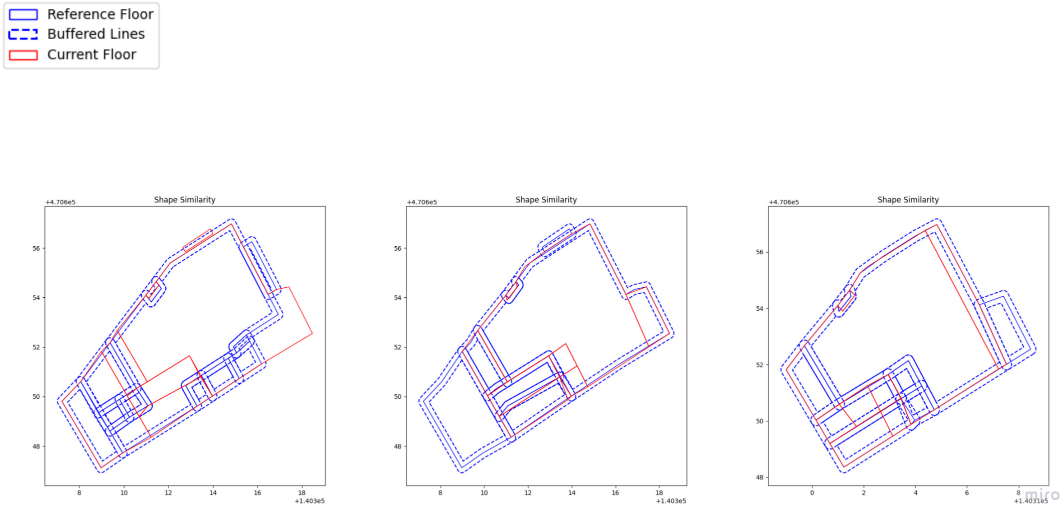


Figure 6.22.: Including snapping with tolerance of 0.2m (storeys 0, 1 and 2)

Limitations

Despite the overall effectiveness, several limitations were identified that impact the accuracy of the storey alignment method.

- **Storey dissimilarity:** Storeys with significantly different layouts in the exterior and interior, have a larger change of being misaligned. The assumption that there exists some similarity between floors in the building is not guaranteed.
- **Unknown accuracy:** The shape similarity score does not directly indicate alignment quality, as such the accuracy of the alignment can not be prompted to the user. This step requires manual verification.
- **Error propagation:** Misalignment at lower levels propagate through the full 3D reconstruction.
- **Discrete step size limitations:** As was the case with georeferencing, the alignment is limited by the discrete translation step sizes in the grid search.
- **Buffer bias:** The shape similarity may favor incorrect alignments if unrelated features have higher overlap in the buffer zone (especially when using exterior walls only).
- **Snapping:** Snapping may introduce distortion and may lead to invalid geometries.

Recommendations

To improve alignment accuracy and robustness in the vectorization process, or further enhancement of the methods, the following items are suggested.

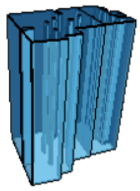
- **Repeating elements:** Using only elements that often repeat, such as elevator shafts and staircases, could improve the alignment. The rooms are labeled so they could be filtered out.

- **Page layout:** Utilize the page layout even further by estimating the distance between each storey on the paper, creating a sort of bounding box around each geometry. By then aligning these bounding boxes, most likely a closer alignment can be achieved. During the vectorization this layout could already be detected.
- **Image based method:** Many image based matching methods exist. These could possibly be used to detect similar features across floors, and then estimate the best transformation to align both images.
- **Rotation of floors in the document** Currently the algorithm also assumes the same rotation for all floors on the division drawing document. In the sample documents this was always the case, but it is not mandatory. To account for this, the search can be expanded to include a rotation search of 4 angles (0, 90, 180, 270) whenever the similarity match is below a certain threshold.

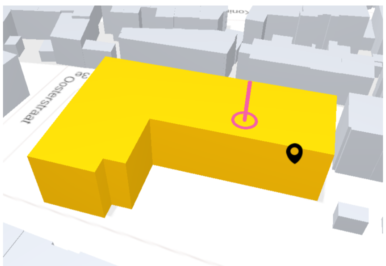
6.2.2. Height Estimation Results

Table 6.4 shows a full comparison of estimated total heights and average floor heights. For buildings with a registered cross-section, storey heights were derived from that data, otherwise values from the 3DBAG were used. Some buildings had multiple entries in 3DBAG.

In total, 4 out of 10 buildings potentially required height thresholding, as described in section 4.2.2, to prevent unrealistic values, of which 2 were very far off.



(a) The height estimation result (43.61m)



(b) The 3DBAG view

(c) The considered "section" geometry

Figure 6.23.: Comparison between estimated and 3DBAG heights for building 9252

In the case of figure 6.23, the estimated building height is this high due to a wrong estimated number of storeys. The storey information text was incorrectly linked to the geometry. This also caused the storey to be considered a section (figure 6.23c), increasing the estimated height even more. The same is the case for building 3723 (6.24c).

The cross section height estimation method is further evaluated in the following sections.

Epsilon Value Influence

The height estimation method that is tested relies on detecting horizontal clusters of vertices in the section drawing. These clusters correspond to potential storeys. An important pa-

Table 6.4.: Average and total estimated storey heights using Section and 3DBAG methods.

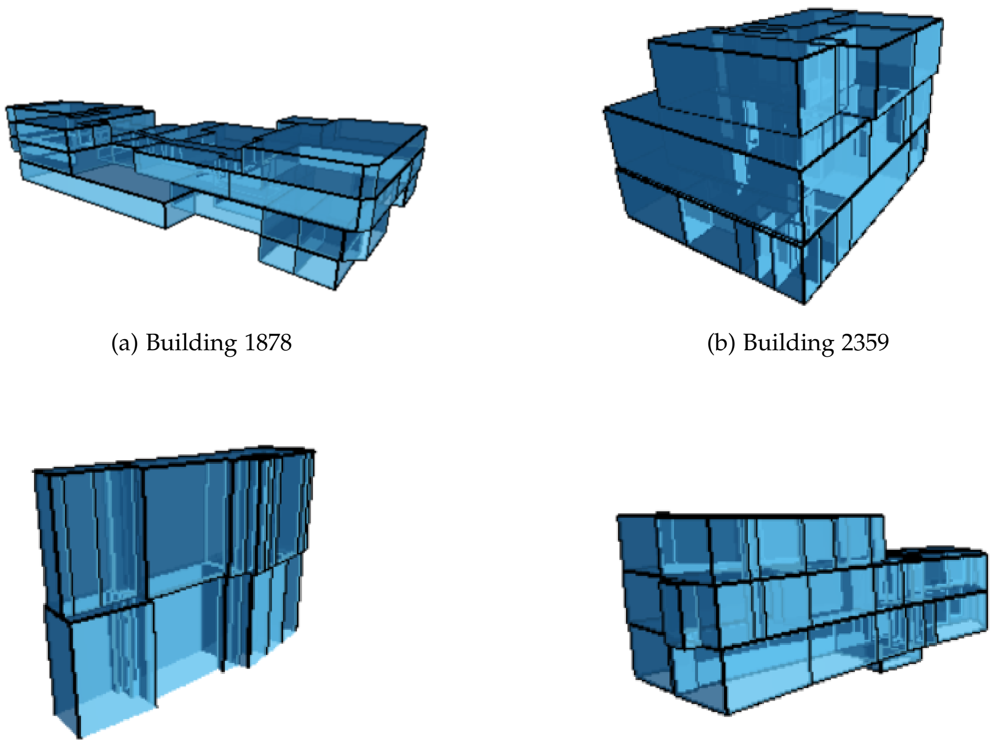
Building ID	**Sec. Total**	**Sec. Avr Storey**	**3DBAG Total**	**3DBAG Avr Storey**	**Notes**
1878/1879	6.88	1.72	9.72	3.24	Multiple sections
1882	-	-	9.40	3.13	
2359	9.46	3.15	9.21, 9.19	3.07, 3.06	2 BAG
2643	-	-	10.40	2.60	
2848	-	-	11.91	2.98	
3211	-	-	5.86	2.93	
3723	21.82	10.91	11.59	11.59	Faulty input
4216	-	-	13.43	3.36	
555/556	12.40	3.10	10.94, 10.47	3.65, 3.49	2 BAG
9252	43.61	43.61	8.69	8.69	Faulty input

rameter in this clustering process is the epsilon value, which defines the distance threshold for vertices to be considered part of the same cluster. Smaller epsilon values lead to more clusters being detected, which may cause overestimation, especially in areas that do not represent actual floors (such as stepped roofs). Larger epsilon values run the risk of merging storeys.

Table 6.5 shows the number of detected storeys (for the buildings which have a correctly linked section), compared to the amount of storeys that have been distinguished as separate floor plans on the division drawing. Figure 6.24 shows the resulting 3D models with the estimated heights from the section.

Table 6.5.: Detected number of storeys per building for different epsilon values

Building ID	ε=0.2	0.4	0.6	1.0	1.4	1.8	2.2	**Amnt Drawn Storeys**
1878/1879	11	6	3	3	2	2	1	4
2359	4	4	4	3	3	3	3	3
3723	28	20	17	9	5	5	1	2*
555/556	8	6	4	4	4	4	3	4



(a) Building 1878 (b) Building 2359

(c) Building 3723 (d) Building 555

Figure 6.24.: Resulting 3D models of buildings using the section for height estimation

From these tests, an epsilon value between 1.0 and 1.8 yielded the best results. In practice the value of 1.4 will be used. Building 2359 and 555/556 are standard examples of buildings with a single correctly drawn cross section. The amount of detected storeys also corresponded with the amount of drawn storeys for a large range of epsilon values.

Note, in case of building 1878/1879 (figure 6.24a), the number of discovered storeys did not correspond to the number of drawn storeys for the tested epsilon values. As described in section 4.2.2, the storey heights are then estimated by using the total height divided by the amount of drawn floor plans, causing an average per floor

This building also has mezzanines halfway between floors, these caused there to be not enough distance between actual floor vertices to be considered a storey. As is seen in figure 6.25, the epsilon value of 0.4 does correctly correspond to the number of subfloors (6). But the height determination of these subfloors was not further explored.

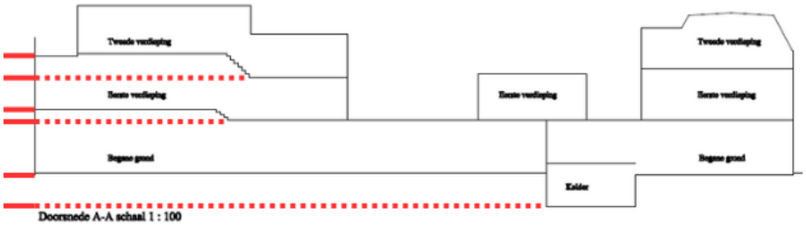


Figure 6.25.: (Sub)floors in building 1878/1879

Comparison to 3DBAG Heights

The heights derived from the cross sections are sensitive to the accuracy and quality of the division drawing, and assumes that all floors are visible and the drawing is horizontally aligned. As such, another dataset is used to perform a sanity check on the resulting height values. The estimated total heights are compared to the 70 percentile height attribute from the 3DBAG dataset 6.6. There was not a reference dataset to compare the storey heights.

Again the same buildings perform well, the green marked buildings have an estimated total height within 5% of the reference 3DBAG height.

Table 6.6.: Comparison of estimated total heights with 3DBAG 70% height values.

Building ID	Estimated Total Height (m)	3DBAG 70% Height (m)
1878/1879	9.72	6.88
2359	9.20	9.46
3723	11.59	18.59
555/556	10.47	10.10

Limitations

The method of estimating storey heights has several limitations.

- **Vertices where there is no floor**: Areas with many vertices in places where there is no floor, like staircases or stepped roofs, might result in an estimation of an extra storey. Currently if there is a mismatch between the calculated and drawn amount of storeys, the total height is averaged over the amount of drawn storeys instead.

- **Incomplete section views**: Sections that do not capture all floors leads to inaccurate height estimations.

- **Sensitive method**: Currently, it only performed well for the two standard case buildings, but not for complex buildings or incorrectly labeled storeys. This indicates that the method might not be robust enough for the variability of division drawings on a larger scale.

- **Thresholding can hide legitimate low or tall ceilings**: Thresholding, a technique to remove outliers, may cause low or very tall ceilings to be excluded, but this is why capping the height is optional.

- **Cannot set height per subfloor**: Because it is unclear which room in the section corresponds to which room in the floor plan, the height can currently only be set per storey. Using the method as developed can help estimate the amount of (sub)floors.

- **3DBAG estimate**: Though the 3DBAG can be used as reference and backup storey height estimation, there is no information included about the interior heights, nor underground storeys.

Recommendations

To improve the accuracy of height estimations, the following recommendations are suggested:

- **Label the section**: It is recommended to label the section drawings as a section during the vectorization process. This can be done by linking the text to this drawings as well, which already includes the word "doorsnede", meaning "cross section".

- **Room detection**: In order to set the height per room, it would be advised to detect which rooms in the section are the same rooms in the floor plan.

- **Section Arrows:** This can be supported by the recognition of arrows which indicate the position of a section in a floor plan.

6.3. BIM Legal Modeling Results

This chapter presents the 3D BIM Legal compliant models developed using the methodology described in section 4.3.

6.3.1. Validation

The geometric validity of the CityJSON files was assessed using the tool *val3dity*. All files were found to be 100% valid, with the exception of one error:

906 PRIMITIVE_NO_GEOMETRY

This error was reported for all instances of *CityObjectGroup* and *Building*. According to the BIM Legal data model, only the *BIMLegalSpaceUnit* have a geometry, which are represented as *BuildingRoom* elements, Higher level objects such as the *CityObjectGroup* and *Building* do not. In the current version of CityJSON it is allowed for these instances to not have a geometry. As noted in the *Val3dity* error documentation, this is expected and therefore does not indicate an actual geometric error.

The validity of the files was also tested when using snapping during the storey alignment, with a threshold of 0.2. Then also the following error was reported for one building:

102 - CONSECUTIVE_POINTS_SAME

This error occurs when two consecutive vertices in a polygon are identical or very close. While it was limited to a single instance in this test, more and different errors may occur when validating snapped results in larger scale testing.

Finally, all files were validated against the CityJSON 2.0 schema using the *cjval* validator. Each file was confirmed to be fully compliant with the CityJSON standard.

6.3.2. Visualization

To support the interpretation of legal spaces in the 3D BIM Legal models, some visualizations were made.

First, the visualization can differentiate between different private apartment units based on the apartment index. These are shown in figure 6.26.

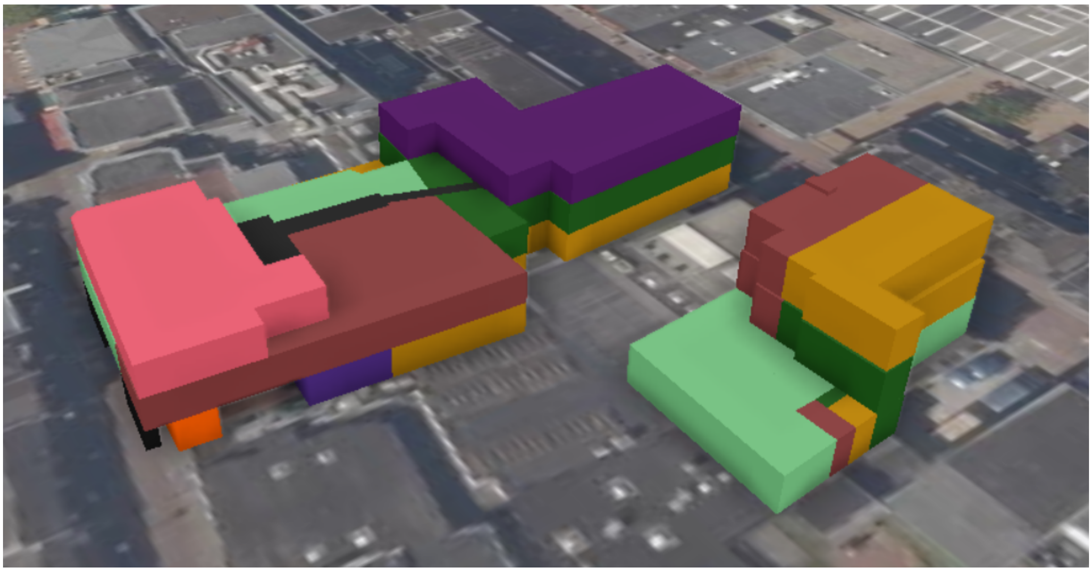


Figure 6.26.: Visualization of individual apartment units

Figure 6.27 show the explicitly the shared spaces.

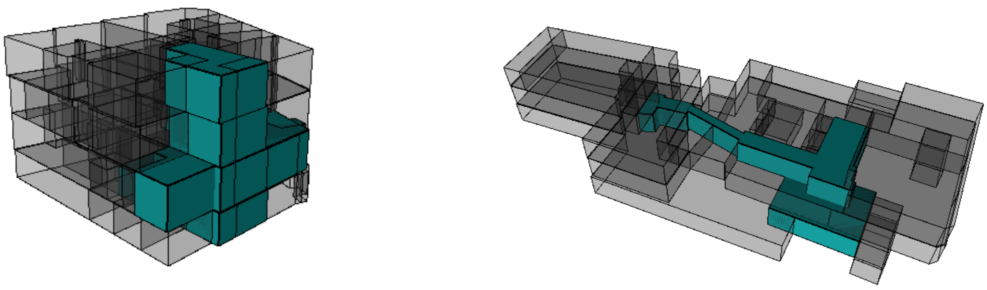


Figure 6.27.: Visualization of shared spaces

Beyond legal space visualization, the textual descriptors of spaces can also be used to show functional use of interior space. This includes the identification of staircases, hallways and toilets. Figure 6.28 shows this functional classification.

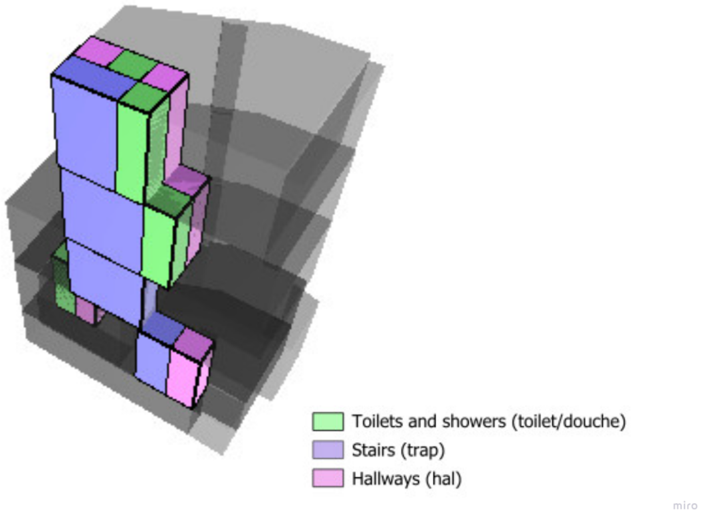


Figure 6.28.: Functional spaces visualized

An overview of all visualized BIM Legal buildings is given in appendix C.

6.4. Pipeline Results

The final pipeline is a result of experimenting to find optimal methods, metrics and parameters. The final chosen techniques per step were:

- **Initialization:**
  - Translation: Centroid alignment
  - Scale: Align area ratio
  - Rotation: Not used
- **2D Alignment:** Exhaustive search using Hausdorff distance and Goodness of Fit, weighted according to geometry type
- **Storey alignment:** Aligning each floor to the floor below by optimizing shape similarity with a buffer of 0.2 meters.
- **Height estimation:** Using the cross section where possible to estimate the heights per storey, assuming the amount of drawn storeys as total storey amount. The 3DBAG is used whenever there is no cross-section.

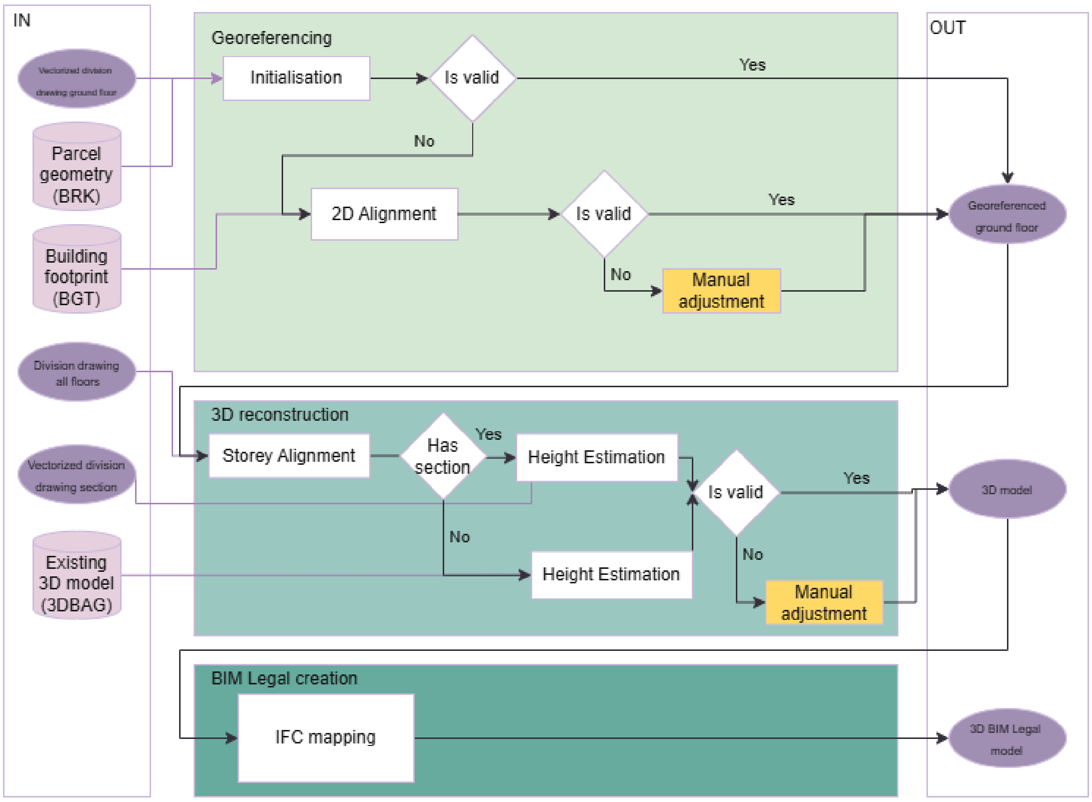


Figure 6.29.: Pipeline result

In theory the entire process from vectorized division drawing to 3D BIM Legal models can be performed automatically. However, whenever intermediate results fail certain checks, they can be manually adjusted. These checks can be seen in figure 6.29. Additionally, if division drawing already align very well in the initialization step, the 2D alignment could be skipped.

Table 6.7 show the thresholds per check.

Step	Score	Threshold	Output
Initialization	Shape similarity and containment	0.85	Georeferenced division drawing
2D alignment	Shape similarity and containment	0.85	Georeferenced division drawing
Height estimation	Height	2.1–3.3 m	3D model height per storey

Table 6.7.: Overview requirements in the pipeline

7. Discussion and Conclusions

This thesis presented a research into the 3D reconstruction of legal apartments from 2D division drawings. An automatic pipeline has been developed, through the evaluation of various methods. The results are discussed in the following sections.

7.1. Research Questions

The conclusions of this research come forth from the objectives presented in section 1.1:

7.1.1. Georeferencing

Data Utilization:

RQ1: What data from the division drawings can be used to support georeferencing, and how valuable is each data type?

The division drawings contain various features valuable for georeferencing. The two main sources are: the parcel ID, and the geometry of the outline of the ground floor. The parcel ID can be used to find candidate BGT buildings that possibly correspond to the apartment in the division drawing, through a spatial intersection of BGT geometries overlapping with the parcel geometries in the BRK. By aligning the outline of the ground floor to the footprint of the BGT, the division drawing can be georeferenced.

In addition, the north arrows and scale text could be used to determine the rotation and scale more quickly and accurately. This requires them to be detected and correctly linked to the corresponding floor plan, which was not the case and therefore this information was not available in the final workflow.

Initialization and Optimization:

2: Which initialization and optimization techniques are most suitable for aligning the division drawing footprints with the building footprints in the Basisregistratie Grootschalige Topografie (BGT)? What is the achievable georeferencing accuracy?

The most effective initialization techniques consists of a combination of centroid alignment, area based scaling and using the north arrow or no rotation.

Optimization was performed through an exhaustive search which evaluates the alignment result of the division drawing to the BGT. Through combinations of transformations to the division drawing (scale, translation and rotation), scores are calculated which are based on the Hausdorff distance and the Goodness of Fit. The exhaustive search has a complexity of $\mathcal{O}(n^4)$ (scale, rotation, translation y and translation x). The performance can benefit greatly from proper initialization, allowing the search ranges for the transformations to be smaller.

Georeferencing accuracy varied between buildings but overall achieved a close alignment. When outside spaces were included in the vectorized division drawing, it resulted in an average containment of 81.5%. When they were removed or non existing it resulted in 95.2% containment. This large difference comes from the difference between the division drawing and the BGT whenever outside spaces are included, as they are not present in the BGT. Despite this, their rotation, scale and translations were approximately correct.

Overall the georeferencing accuracy depends on the similarity between the division drawings and their BGT counterparts.

7.1.2. 3D Reconstruction

Data Utilization:

RQ3: What data from the division drawings can be used to support 3D reconstruction, and what is their value?

Both the external and interior geometries are essential for storey alignment, allowing storeys to align to the storey below. In order to know the order of the vertical storey stack, the text below each floor plan is important, as this indicates its position. These texts must also be properly linked to their geometry.

In determining the height of the storeys, the cross section can be of great help. Allowing for different storey heights to be determined, rather than an average based on the total height.

Extrusion and Positioning:

RQ4: How can floor heights be estimated from division drawings, and how can the floor plans be accurately positioned in 3D space?

The position of storeys in 3D relied on aligning each floor plan to the one below, using shape similarity to determine the optimal relative positions. Using both interior and exterior worked better than using only the exterior. And utilizing the layout on the division drawing also improved the model. While this worked well in most cases, non-similar geometries can still be positioned in the wrong spot (with a maximum y-axis error of 0.5 m). Error propagation can occur when there is a misalignment on a lower floor.

The height storey height estimation also depends on proper vectorization. The method utilizing the section performed well, though this needs more refinement with more sample division drawings. Seven out of eleven buildings could be extruded directly. Two needed capping to be within standard height values. The remaining two buildings had vectorization flaws causing faulty results.

7.1.3. BIM Legal

Data Structure:

RQ5: How can the generated data be structured according to the BIM Legal data model? What information is required to produce a valid BIM Legal model?

Generated geometries were structured in accordance with the BIM Legal model by defining private apartments and shared spaces. CityJSON was chosen as appropriate alternative to IFC for the format of the BIM Legal model. This format supports the hierarchical structure of BIM Legal, can be georeferenced, supports 3D geometry, and can be viewed in standard GIS software. Additional attributes including the cadastral parcel number, apartment index, space description and a georeferencing accuracy score, have been added to each room.

Pipeline Improvement:

RQ6: How can the vectorization of division drawings be improved to support automated 3D reconstruction? How well do the resulting models integrate with the BIM Legal standard?

The quality of vectorization is a bottleneck in the pipeline. Recommendations for improving the quality of the vectorization process to be able to obtain better 3D results are: automatic detection and preservation of north arrows, scale bars, and text annotations per floor plan and cross section. It is also recommended to extract the full parcel text, with the parcel IDs separated by a dash. This accounts for the possibility of multiple parcels on the division drawings. The recognition of arrows indicating the position of a cross section in the floor plans would also aid in determining the rooms shown in the cross section. Which could then allow each room to be estimated to its own height as determined from the cross section. Finally, a major source of error is the misalignment of the division drawings and the BGT when outside spaces are included in the division drawings, as these are not included in the BGT. Sometimes the outside spaces have been (correctly) vectorized, but other times they were removed. To create a smoother alignment, these spaces could be recognized during vectorization based on their label (for example ”garden”, ”parcel” or ”balcony”) and tagged so they can be temporarily removed during alignment. This would ensure the division drawing geometries are as close as possible to the BGT, after which all legal spaces are visualized.

7.2. Discussion

7.2.1. Limitations of this research

The evaluation of the developed method was based on a limited dataset consisting of only 10 sample buildings. While this was sufficient to develop a workflow, the sample size is not representative of the variety of real world division drawings. Though the methodology was designed to be robust, and tested against manufactured situations, the robustness of the method has to be tested across a larger range of division drawings to account for more possible cases. Another limitation stems from the division drawings themselves. While drawn to scale, these drawings are schematic representations of legal spaces, rather than detailed architectural plans. Especially the vertical alignment of floors is difficult because of this. It is assumed that consistent elements such as load bearing walls provide guides to the alignment of floors, but the geometries in the division drawing do not necessarily indicate walls. The division drawing can also include spaces like private gardens, which can lack semantic labels and are modeled in 3D just like the building. These spaces are also not included in the BGT footprint, this difference can cause misalignment.

The only reference for linking the division drawings to geospatial data is the parcel ID. There are no coordinate references in the drawing. The parcel ID enables the retrieval of the BGT buildings through spatial overlay.

Additionally, the division drawings vary greatly in their content. Some include cross sections or annotations providing room descriptions, while others consist only of floor plans. The accuracy of the division drawing is also impacted by whether it was hand-drawn, or digitally, as small flaws in the geometry are also vectorized.

Another technical limitation arises from how spaces are modeled. During vectorization, the drawn geometries are estimated as polylines. This means that rounded geometries are represented as lines rather than curves. Additionally, the 3D spaces are created from simple extrusion due to the lack of consistent 3D information. The models are therefore restricted to an LoD1+, where features such as sloped or curved roofs can not be represented. The current method of estimating storey heights also does not allow for rooms to be extruded to individual heights, this is performed per storey.

7.2.2. Implications of the BIM Legal Models

The BIM Legal models produced in this research differ from those generated from existing BIM files. Firstly, they are created at a lower level of detail, as previously mentioned. Secondly, the models are georeferenced using global coordinates derived from aligning to the BGT. In contrast, a big challenge of IFC based BIM Legal modeling is the fact that they are positioned locally and have to be georeferenced either manually or through alternative methods that are being researched. Thirdly, unlike BIM models which represent physical structures, the BIM Legal models from division drawings represent legal spaces and building elements are not part of the division drawing. Therefore, restrictions on physical elements such as walls can be included in the IFC based BIM Legal model, but not in the division drawing based models without making assumptions about the thickness of these elements.

The value of the resulting models lies in their ability to visualize legal spaces in 3D. This makes it possible to explore and communicate private and shared ownership areas. However, due to the schematic nature of the input data and the estimation involved in the modeling pipeline, no legal claims can be made on the dimensional accuracy of the models.

7.3. Contribution

Despite the limitations, the developed pipeline has various applications and contributions to the field.

- The pipeline was developed to generate 3D BIM Legal models from division drawings, automatically as far as possible. There was no known open solution to this yet, and it has been achieved through this research. The developed process can be used as a proof-of-concept, and can provide a starting point for a large scale future conversion pipeline.
- This research presents an overview of literature and methods related to the 3D reconstruction of division drawings, which to my knowledge did not exist yet.
- The methodology to align corresponding datasets, with some degree of similarity between them, had not been widely researched yet. This could be used to align other kinds of non-georeferenced polygon data like field sketches, to a reference cadastral dataset.
- The developed storey alignment methodology had significant limitations but could be useful in aligning (hand-drawn) architectural floor plans, which do represent physical objects.
- This research also serves as a proof of concept for successfully using CityJSON as a data format for BIM Legal modeling.
- This research presents an additional step towards a 3D cadaster.

7.4. Future Work

There are several areas for future research.

Inclusion of architectural drawings: One of the main limitations of the results is the fact that division drawings are not precise representations of apartment buildings. A potential research direction is to combine the division drawings with more detailed architectural plans. This would enable the legal division to be tied to physical boundaries. As well as improving the possible level of detail to LoD2+, like BIM Legal from IFC. It would also allow the display of legal spaces that are not drawn on the architectural floor plans, like gardens. Potentially with this integration, the models could be on par with IFC based BIM Legal models.

User interface: The current workflow was designed as a mostly automated process, with manual verification steps where needed. However, the accuracy and usability of this workflow could be improved through the development of an interactive interface. This could support step-by-step validation of the reconstruction, allowing users to correct errors in the vectorization, georeferencing, and storey alignment.

Use case expansion through visualization: Although the current models were developed for the visualization of legal spaces, the reconstructed 3D units also have value beyond this:

- Division drawings sometimes include basements or underground garages. These are not present in other, more common, building datasets made from point clouds, like the 3Dbag. Future research could focus on incorporating these models into a city model, including underground structures. This has applications in infrastructure planning.

- For most division drawings, the units include some sort of textual description of the function of the space. When these are included, the staircases and hallways can be visualized separately in 3D. This can be used for quick overview of the internal structure for safety assessment.
- These descriptions can also be used to visualize specific functional spaces, like toilets or utility rooms. This can support maintenance planning.

A. Example division drawing

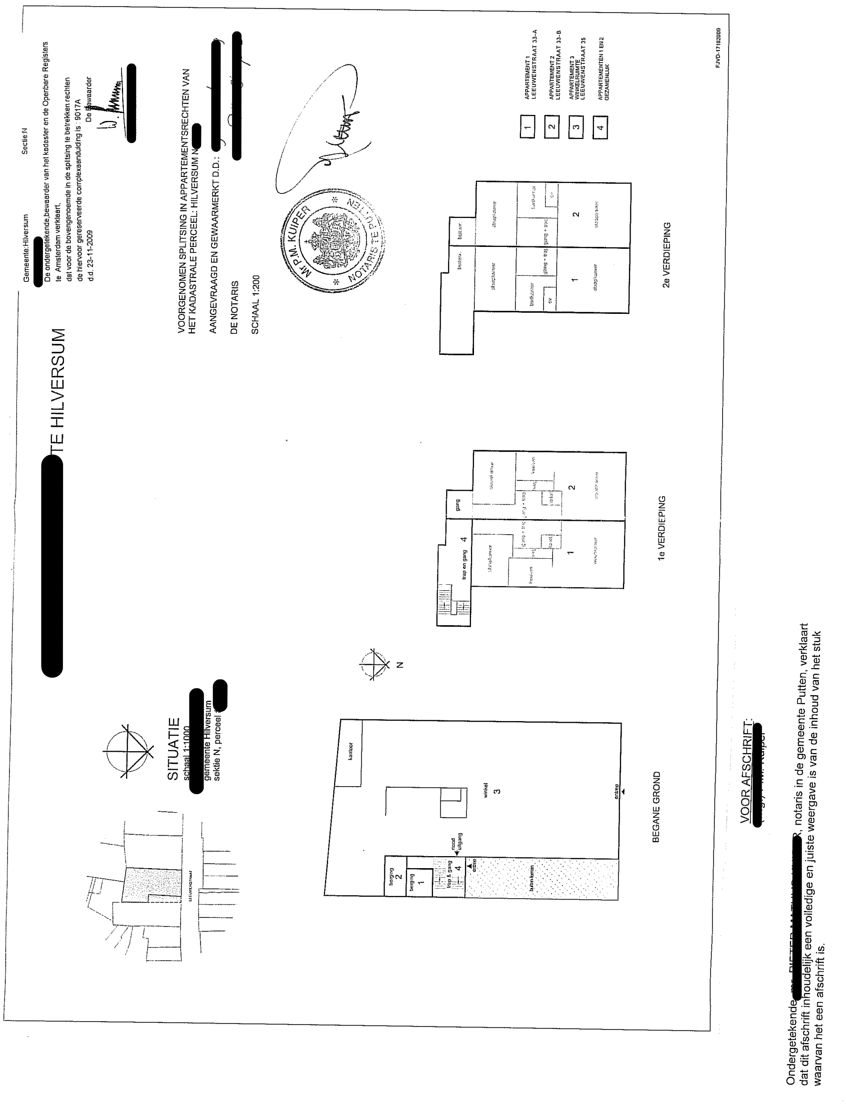


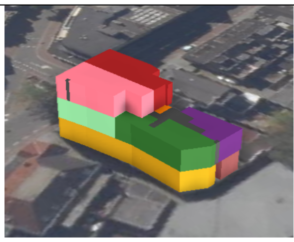
Figure A.1.: A division drawing

B. Example CityJSON BIM Legal file

```
{
  "type": "CityJSON",
  "version": "2.0",
  "CityObjects": {
    "id_1": {
      "type": "CityObjectGroup",
      "attributes": {
        "name": "BIMLegalApartmentComplex",
                "parcel_id": "HVS00_N_00555"
      },
      "children": [
        "id_2"
      ]
    },
    "id_2": {
      "type": "Building",
      "attributes": {
        "apartmentComplexIndex": "AC-01"
      },
      "children": [
        "id_3", ...
      ],
      "parents": [
        "id_1"
      ]
    },
    "id_3": {
      "type": "BuildingUnit",
      "attributes": {
        "apartmentIndex": "1"
      },
      "children": [
        "id_4", ...
      ],
      "parents": [
        "id_2"
      ]
    },
    "id_5": {
      "type": "BuildingUnit",
      "attributes": {
        "name": "SharedPart",
      },
      "children": [
        "id_6",...
```

```
      ],
      "parents": [
        "id_2"
      ]
    },
    "id_4": {
      "type": "BuildingRoom",
      "attributes": {
        "name": "bedrijfsruimte",
        "extrusion_height": 3.3,
        "function": "bedrijfsruimte",
        "appartmentIndex": 1
                "georef_acc": "86.5",
                "bimLegalSpaceUnitType": "m",
                "level": 0,
      },
      "geometry": [
        {
          "type": "MultiSurface",
          "lod": "1",
          "boundaries": [...]
      "parents": [
        "id_3"
      ]
    },
```

C. Final BIM Legal models

ID	Final BIM Legal model
9252*	
555/556	
1878/1879	
1882	
2359	

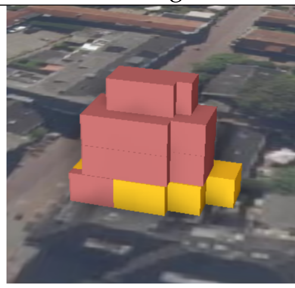
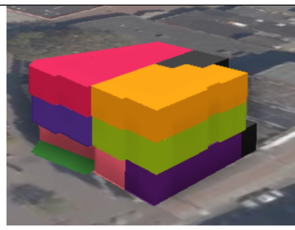
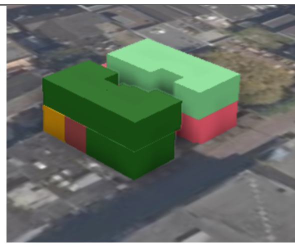
ID	Final BIM Legal model
2643	
2848	
3211	
3723*	
4216	

Table C.1.: All final BIM legal models, coloured according to the apartment index
*These buildings had extreme values beyond the height thresholds (2.1-3.3) and were automatically increased or lowered to these values.

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Colophon

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