1. Introduction

This is a complete template for the MSc Geomatics thesis. It contains all the parts that are required and is structured in such a way that most/all supervisors expect. Observe that the MSc Geomatics at TU Delft has no formal requirements, how the document looks like (fonts, margins, headers, etc) is entirely up to you.

We basically took the template `KOMA-Script scrbook`, added the front/back matters (cover page, copyright, abstract, etc.), and gave examples for the insertion of figures, tables and algorithms.

It is not an official template and it is not mandatory to use it.

But we hope it will encourage everyone to use LaTeX for writing their thesis, and we also hope that it will *discourage* some from using Word.

If you run into mistakes/problems/issues, please report them on the GitHub page, and if you fix an error, then please submit a pull request.

https://github.com/tudelft3d/msc_geomatics_thesis_template.

1.1. How to get started with LaTeX?

Follow the Overleaf's Learn LaTeX in 30min (https://www.overleaf.com/learn/latex/Learn_LaTeX_in_30_minutes) to start.

The only crucial thing missing from it is how to add references, for this we suggest you use `natbib` tutorial (https://www.overleaf.com/learn/latex/Bibliography_management_with_natbib).

1.2. Cross-references

The command `autoref` can be used for chapters, sections, subsections, figures, tables, etc.

Chapter 1 is what you are currently reading, and its name is Introduction. Section 1.9 is about pseudo-code, and Section 1.3.1 is about something else. The next chapter (**??**), is on page **??**.

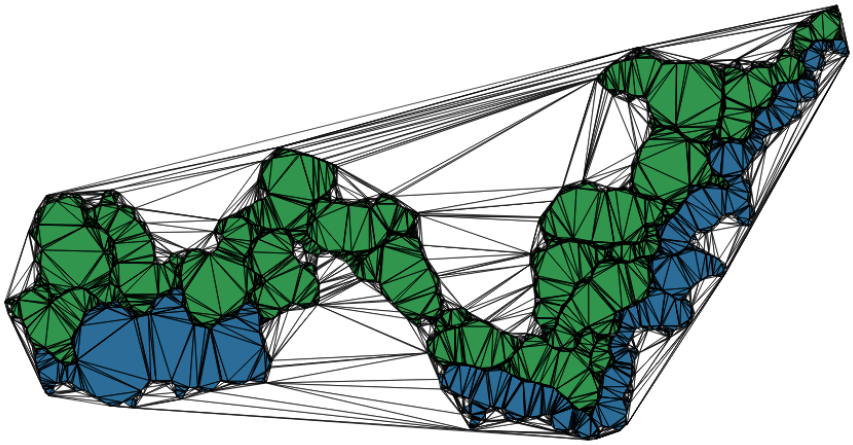


Figure 1.1.: One nice figure

1.3. Figures

Figure 1.1 is a simple figure. Notice that all figures in your thesis should be referenced to in the main text. The same applies to tables and algorithms.

It is recommended *not* to force-place your figures (e.g. with commands such as: `\newpage` or by forcing a figure to be at the top of a page). LaTeX usually places the figures automatically rather well. Only if at the end of your thesis you have small problem then can you solve them.

As shown in Figure 1.2, it is possible to have two figures (or more) side by side. You can also refer to a subfigure: see Figure 1.2b.

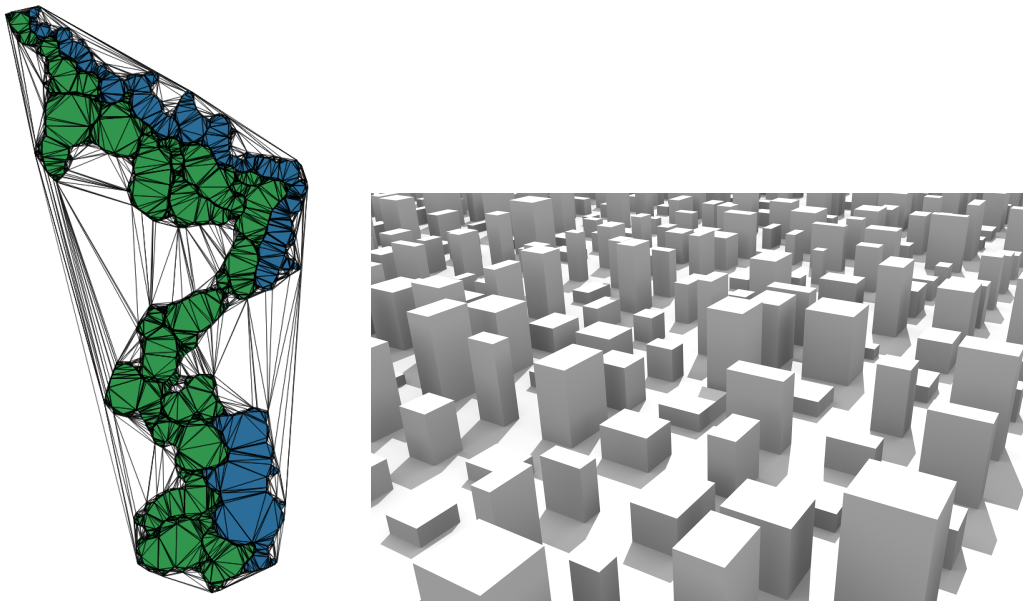
1.3.1. Figures in PDF are possible and even encouraged!

If you use Adobe Illustrator or Ipe you can make your figures vectorial and save them in PDF.

You include a PDF the same way as you do for a PNG, see Figure 1.3,

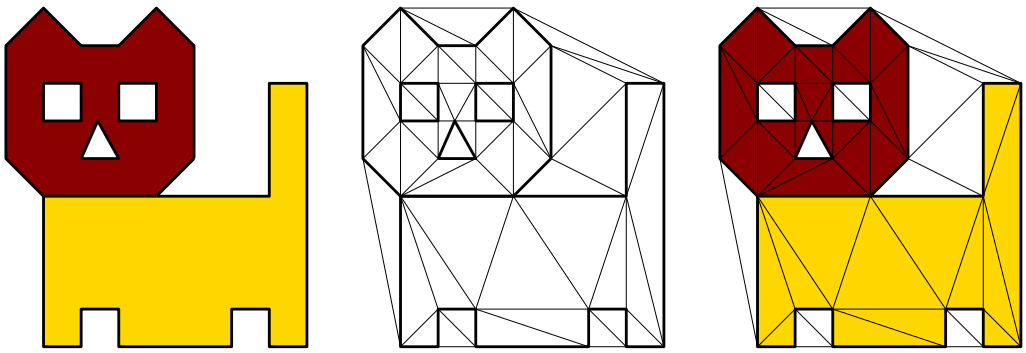
1.4. How to add references?

References are best handled using BibTeX. See the `myreferences.bib` file. A good cross-platform reference manager is JabRef.



(a) (b)

Figure 1.2.: Two figures side-by-side. (a) A triangulation of 2 polygons. (b) Something not related at all.



(a) 2 polygons (b) CDT (c) with colours

Figure 1.3.: Three PDF figures.

	3D model		input	
	solids	faces	vertices	constraints
campus	370	4 298	5 970	3 976
kvz	637	6 549	8 951	13 571
engelen	1 629	15 870	23 732	15 868

Table 1.1.: Details concerning the datasets used for the experiments.

1.5. Footnotes

Footnotes are a good way to write text that is not essential for the understanding of the text[1].

1.6. Equations

Equations and variables can be put inline in the text, but also numbered.

Let S be a set of points in $\mathbb{R}^d$. The Voronoi cell of a point $p \in S$, defined $\mathcal{V}_p$, is the set of points $x \in \mathbb{R}^d$ that are closer to p than to any other point in S; that is:

$$\mathcal{V}_p = \{x \in \mathbb{R}^d \mid \|x - p\| \leq \|x - q\|, \forall q \in S\}. \tag{1.1}$$

The union of the Voronoi cells of all generating points $p \in S$ form the Voronoi diagram of S, defined VD(S).

1.7. Tables

The package `booktabs` permits you to make nicer tables than the basic ones in LaTeX. See for instance Table C.1.

1.8. Plots

The best way is to use matplotlib, or its more beautiful version (seaborn). With these, you can use Python to generate nice PDF plots, such as that in Figure 1.4.

In the folder `./plots/`, there is an example of a CSV file of the temperature of Delft, taken somewhere. From this CSV, the plot is generated with the script `createplot.py`.

[1] but please do not overuse them

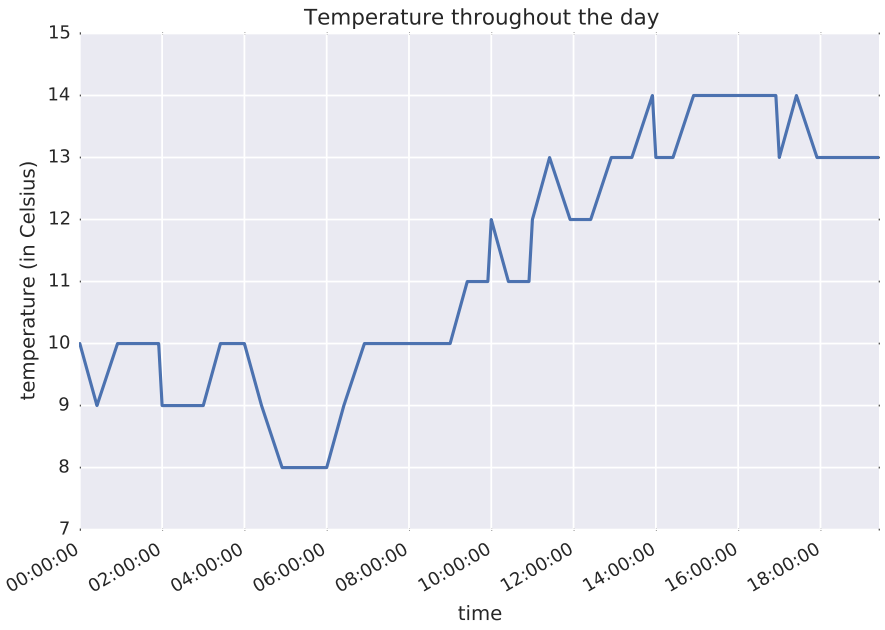


Figure 1.4.: A super plot

1.9. Pseudo-code

Please avoid putting code (Python, C++, Fortran) in your thesis. Small excerpt are probably fine (for some cases), but do not put all the code in an appendix. Instead, put your code somewhere online (e.g. GitHub) and put *pseudo-code* in your thesis. The package `algorithm2e` is pretty handy, see for instance the Algorithm 1.1. All your algorithms will be automatically added to the list of algorithms at the begining of the thesis. Observe that you can put labels on certain lines (with) and then reference to them: on line 4 of the Algorithm 1.1 this is happening.

If you want to put some code (or XML for instance), use the package `listings`, e.g. you can wrap it in a Figure so that it does not span over multiple pages.

1.10. Acronyms

If you want to have a list of acronyms you use in your thesis, use the `acronym` package. The first time you speak about **gis!** (**gis!**), it will be spelled out. Further use, **gis!**, you'll get the acronym plus a hyperlink to the list in the preambule of the thesis.

Add yours to `front/acronyms.tex`. Notice that only these used are printed, e.g. **dt!** (**dt!**) and **tin!** (**tin!**).

Algorithm 1.1: WALK ($\mathcal{T}$, τ, p)

Input: A Delaunay tetrahedralization $\mathcal{T}$, a starting tetrahedron τ, and a query point p
Output: τ_r: the tetrahedron in $\mathcal{T}$ containing p

```
1 while τ_r not found do
2     for i ← 0 to 3 do
3         σ_i ← get face opposite vertex i in τ;
4         if Orient(σ_i, p) < 0 then
5             τ ← get neighbouring tetrahedron of τ incident to σ_i;
6             break;
7     if i = 3 then
          // all the faces of τ have been tested
8         return τ_r = τ
```

```
<gml:Solid>
  <gml:exterior>
    <gml:CompositeSurface>
      <gml:surfaceMember>
        <gml:Polygon>
          <gml:exterior>
            <gml:LinearRing>
              <gml:pos>0.000000 0.000000 1.000000</gml:pos>
              <gml:pos>1.000000 0.000000 1.000000</gml:pos>
              <gml:pos>1.000000 1.000000 1.000000</gml:pos>
              <gml:pos>0.000000 1.000000 1.000000</gml:pos>
              <gml:pos>0.000000 0.000000 1.000000</gml:pos>
            </gml:LinearRing>
          </gml:exterior>
          <gml:interior>
          ...
      </gml:surfaceMember>
    </gml:CompositeSurface>
  </gml:interior>
</gml:Solid>
```

Figure 1.5.: Some GML for a `gml:Solid`.

1.11. TODO notes

At P4 or for earlier drafts, it might be good to let the readers know that some part need more work. Or that a figure will be added.

The package todonotes is perfect for this.

adding holders for figures is also possible

A summary of all TODOs in the thesis can even be generated.

1.12. Miscellaneous

In the file `mysettings.tex`, there are some handy shortcuts.

This is the way to properly write these abbreviations, i.e. so that the spacing is correct. And this is how you use an example, e.g. like this.

You should use one - for an hyphen between words ('multi-dimensional'), two -- for a range between numbers ('1990–1995'), and three --- for a punctuation in a sentence ('I like—unlike my father—to build multi-dimensional models').

2. Related work

This chapter reviews existing work related to 3D city model formats, focusing on their storage efficiency, query performance, and suitability for web-based applications. The review provides context for understanding the design decisions behind FlatCityBuf and positions it within the landscape of geospatial data formats.

3. Theoretical background

3.1. Zero-copy

3.2. Endianness

3.3. Indexing algorithms

3.3.1. Indexing Strategy Evaluation

Several indexing strategies were evaluated to determine the most appropriate approach for the FlatCityBuf format:

Table 3.1.: Comparison of Indexing Strategies

Strategy	**Exact Match**	**Range Query**	**Space Efficiency**	**HTTP Suitability**
Hash Tables	$O(1)$	Poor	Medium	Poor
Sorted Array	$O(\log n)$	Good	Excellent	Limited
Binary Search Tree	$O(\log n)$	Good	Good	Limited
B-tree/B+tree	$O(\log_B n)$	Excellent	Good	Excellent

Initial implementation used a sorted array with binary search for its simplicity and space efficiency. However, performance testing revealed significant I/O latency issues when accessing this structure over HTTP, as each binary search step potentially required a separate HTTP request. This insight led to a re-evaluation of the indexing approach.

3.4. Binary Search

Binary search is a fundamental algorithm for finding elements in a sorted array. The classic implementation follows a simple approach: compare the search key with the middle element of the array, then recursively search the left or right half depending on the comparison result [**?**].

The time complexity of binary search is logarithmic—the height of the implicit binary search tree is $\log_2(n)$ for an array of size n. While this is theoretically efficient, the actual performance suffers when implemented on modern hardware due to memory access patterns. Each comparison requires the processor to fetch a new element, potentially causing a cache miss. In the worst case, the number of memory read operations will be proportional to the

Algorithm 3.1: Classic Binary Search

Input: A sorted array, a target value, left and right bounds
Output: The index where the target value should be inserted

```
1 while left < right do
2     mid ← (left + right) / 2;
3     if array[mid] ≥ target then
4         right ← mid;
5     else
6         left ← mid + 1;
7 return left
```

height of the tree, with each read potentially requiring access to a different cache line or disk block [**?**].

This inefficiency is particularly problematic when binary search is implemented on external memory or over HTTP, where each access incurs significant latency. The sorted array representation with binary search does not take advantage of CPU cache locality, as consecutive comparisons frequently access distant memory locations.

3.4.1. Eytzinger Layout

While preserving the same algorithmic idea as binary search, the Eytzinger layout (also known as a complete binary tree layout or level-order layout) rearranges the array elements to match the access pattern of a binary search [**?**]. Instead of storing elements in sorted order, it places them in the order they would be visited during a level-order traversal of a complete binary tree.

This layout significantly improves memory access patterns. When the array is accessed in the sequence of a binary search operation, adjacent accesses often refer to elements that are in the same or adjacent cache lines. This spatial locality enables effective hardware prefetching, allowing the CPU to anticipate and load required data before it is explicitly accessed, thus reducing latency [**?**].

The Eytzinger layout can provide up to 4× performance improvement over a standard binary search implementation due to better utilization of the CPU cache hierarchy, despite having the same algorithmic time complexity. This makes it particularly valuable for applications where search operations need to be performed repeatedly on static datasets.

3.5. Static B+Tree

While the Eytzinger layout improves cache utilization for binary search, the number of memory read operations remains proportional to the height of the tree—$\log_2(n)$ for n elements. This is still suboptimal for large datasets, especially when the access pattern involves disk I/O or remote data access [**?**].

The Static B+Tree (S+Tree) approach addresses this limitation by fetching multiple keys at once instead of single elements. This aligns with modern hardware characteristics where:

- The latency of fetching a single byte is comparable to fetching an entire cache line (64 bytes)
- Disk and network I/O operations have high initial latency but relatively low marginal cost for additional bytes
- CPU cache lines typically hold multiple array elements (e.g., 16 integers in a 64-byte cache line)

The key insight is that loading a block of B elements at once and performing a local search within that block can reduce the total number of cache misses or disk accesses to $\log_B(n)$ instead of $\log_2(n)$—a significant reduction for large datasets [**?**].

Unlike traditional B+Trees that use explicit pointers between nodes, the Static B+Tree uses an implicit structure where child positions are calculated mathematically. This is possible because:

- The tree is constructed once and never modified (static)
- The number of elements is known in advance
- The tree can be maximally filled with no empty slots
- Child positions follow a predictable pattern based on the block size

For a Static B+Tree with block size B, a node with index k has its children at indices calculated by a simple formula: $\text{child}_i(k) = k \cdot (B + 1) + i + 1$ for $i \in [0, B]$ [**?**]. This eliminates the need to store and fetch explicit pointer values, further reducing memory usage and improving cache efficiency.

The S+Tree layout achieves up to 15× performance improvement over standard binary search implementations while requiring only 6-7% additional memory [**?**]. This makes it particularly valuable for applications that perform frequent searches on large, relatively static datasets, especially when accessed over high-latency connections such as disk, network, or HTTP.

3.6. FlatBuffers Framework

FlatBuffers, developed by **?**, is a cross-platform serialisation framework designed specifically for performance-critical applications with a focus on memory efficiency and processing speed. Unlike traditional serialisation approaches, FlatBuffers implements a zero-copy deserialisation mechanism that enables direct access to serialised data without an intermediate parsing step [**?**], as discussed in Section 3.1. This characteristic is particularly advantageous for large geospatial datasets where parsing overhead can significantly impact performance.

3.6.1. Schema-Based Serialisation

FlatBuffers employs a strongly typed, schema-based approach to data serialisation. The workflow involves:

1. Definition of data structures in schema files with the `.fbs` extension
2. Compilation of schema files using the FlatBuffers compiler (`flatc`)
3. Generation of language-specific code for data access
4. Implementation of application logic using the generated code

This schema-first approach enforces data consistency and type safety, which is essential to be processed in various programming languages and environments. The generated code provides memory-efficient access patterns to the underlying binary data without requiring full deserialisation. FlatCityBuf utilises this capability to achieve a balance between parsing speed and storage efficiency.

The FlatBuffers compiler supports code generation for multiple programming languages, including C++, Java, C#, Go, Python, JavaScript, TypeScript, Rust, and others, facilitating cross-platform interoperability [**?**]. This extensive language support enables developers to work with FlatBuffers data in their preferred environment. For FlatCityBuf, Rust was selected as the primary implementation language due to its performance characteristics and memory safety guarantees.

3.6.2. Data Type System

FlatBuffers provides a comprehensive type system that balances efficiency and expressiveness [**?**]:

- **Tables**: Variable-sized object containers that support:
  - Named fields with type annotations
  - Optional fields with default values
  - Schema evolution through backward compatibility
  - Non-sequential field storage for memory optimisation
- **Structs**: Fixed-size, inline aggregates that:

  - Require all fields to be present (no optionality)
  - Are stored directly within their containing object
  - Provide faster access at the cost of schema flexibility
  - Optimise memory layout for primitive types
- **Scalar Types**:
  - 8-bit integers: `byte` (int8), `ubyte` (uint8), `bool`
  - 16-bit integers: `short` (int16), `ushort` (uint16)
  - 32-bit values: `int` (int32), `uint` (uint32), `float`
  - 64-bit values: `long` (int64), `ulong` (uint64), `double`
- **Complex Types**:
  - `[T]`: Vectors (single-dimension arrays) of any supported type
  - `string`: UTF-8 or 7-bit ASCII encoded text with length prefix
  - References to other tables, structs, or unions
- **Enums**: Type-safe constants mapped to underlying integer types
- **Unions**: Tagged unions supporting variant types

3.6.3. Schema Organisation Features

In addition to the data type system, FlatBuffers provides several key features for organising complex schemas:

- **Namespaces** (`namespace FlatCityBuf;`) create logical boundaries and prevent naming collisions
- **Include Mechanism** (`include "header.fbs";`) enables modular schema design across multiple files
- **Root Type** (`root_type Header;`) identifies the primary table that serves as the entry point for buffer access

These features were essential for FlatCityBuf's implementation, enabling modular schema development with separate root types for header and feature components while maintaining consistent type definitions across files.

move this section to theoretical background?

3.6.4. Binary Structure and Memory Layout

FlatBuffers organises serialised data in a flat binary buffer with the following characteristics:

- **Prefix-based vtables** that enable field access without full parsing
- **Offset-based references** that allow direct navigation within the buffer
- **Aligned memory layout** optimised for CPU cache efficiency
- **Endian-aware serialisation** supporting both little and big-endian platforms

For complex data structures like 3D city models, FlatBuffers allows for modular schema composition through file inclusion. This capability enabled the separation of FlatCityBuf's schema into logical components (`header.fbs`, `feature.fbs`, `geometry.fbs`, etc.) while maintaining efficient serialisation. In our implementation, the `Header` and `CityFeature` tables serve as root types that anchor the overall data structure.

4. Methodology

This chapter presents the design and implementation of FlatCityBuf, a cloud-optimised binary format for 3D city models based on CityJSON. The proposed approach addresses the limitations of existing formats through efficient binary encoding, spatial indexing, attribute indexing, and support for partial data retrieval.

4.1. Overview

4.1.1. Methodology Approach

Current 3D city model formats like CityGML, CityJSON, and CityJSONSeq (also **cjseq!** (**cjseq!**)) exhibit limitations in cloud environments with large-scale datasets, including retrieval latency, inefficient spatial querying without additional software support, and insufficient support for partial data access.

This research methodology addresses these limitations through three interconnected objectives:

1. Development of a binary encoding strategy using FlatBuffers that preserves semantic richness while achieving faster read performance
2. Implementation of dual indexing mechanisms—spatial (Packed Hilbert R-tree) and attribute-based (Static B+tree)—that accelerate query performance
3. Integration of cloud-native data access patterns through HTTP Range Requests, enabling partial data retrieval

4.1.2. File Structure Overview

The FlatCityBuf format implements a structured binary encoding with five sequentially arranged components:

- **Magic bytes**: Eight-byte identifier ('FCB
  0') for format validation
- **Header section**: Contains metadata, schema definitions, and CityJSON properties
- **Spatial index**: Implements a Packed Hilbert R-tree for efficient geospatial queries
- **Attribute index**: Utilises a Static B+tree for accelerated attribute-based filtering
- **Features section**: Stores city objects encoded as FlatBuffers tables

Figure 4.1.: Physical layout of the FlatCityBuf file format, showing section boundaries and alignment considerations for optimised range requests

This sequence-based structure enables incremental file access through HTTP Range Requests—critical for cloud-based applications where minimising data transfer is essential. Each section is designed with explicit consideration for alignment boundaries to optimise I/O operations.

4.1.3. Note on Binary Encoding

add reference why these two

FlatCityBuf follows two key conventions for encoding binary data throughout the file format:

1. **Size-prefixed FlatBuffers**: All FlatBuffers records (header and features) include a 4-byte unsigned integer prefix indicating the buffer size. This enables programs to know the size of the record without parsing the entire content. The FlatBuffers API implements this through `finish_size_prefixed` or equivalent language-specific methods.
2. **Little-endian encoding**: For data encoded outside FlatBuffers records (particularly in spatial and attribute indices), little-endian byte ordering is consistently applied. This includes numeric values such as 32-bit and 64-bit integers, floating-point numbers, and offset values within indices.

add reference

These conventions ensure consistency across the file format and maximise compatibility with modern CPU architectures, most of which use little-endian byte ordering. The size-prefixing mechanism is particularly important for cloud-based access patterns, as it facilitates precise HTTP Range Requests when retrieving specific file segments.

4.2. Magic Bytes

The magic bytes section comprises the first eight bytes of the file:

check detail again

- The first four bytes contain the ASCII sequence 'FCB 0' (0x46 0x43 0x42 0x00) serving as an immediate identifier
- The remaining four bytes follow a pattern similar to FlatGeoBuf [**?**], with byte 5-6 containing the major version (currently 01), followed by ASCII 'FB' (0x46 0x42) representing 'FlatBuffers', and byte 8 containing patch version (currently 00)

This signature design enables applications to validate file type and version compatibility without parsing the entire header content. The approach was directly inspired by FlatGeoBuf's methodology, which uses 'FGB' (F, G, B characters) in its magic bytes to indicate 'FlatGeoBuf' [**?**].

4.3. Header Section

The header section encapsulates metadata essential for interpreting the file contents, implemented as a size-prefixed FlatBuffers-serialised `Header` table. The header serves a dual purpose: it maintains compatibility with CityJSON by encoding the equivalent of the first line of a CityJSONSeq stream [**?**]—which contains the root CityJSON object with metadata, coordinate reference system, and transformations—while adding FlatCityBuf-specific extensions for optimised retrieval and indexing. The full schema definition for the header can be found in Appendix C.

In a CityJSONSeq file, the first line contains a valid CityJSON object with empty `CityObjects` and `vertices` arrays but with essential global properties like `transform`, `metadata`, and `version`. The FlatCityBuf header encodes these same properties alongside additional indexing information required for cloud-optimised access patterns.

4.3.1. CityJSON Metadata Fields

Here are the core header fields with their data types and significance:

- **version** - *string (required)* - CityJSON version identifier (e.g., "2.1"), required field from CityJSON specification [**?**]
- **transform** - *Transform struct* - Contains scale and translation vectors enabling efficient storage of vertex coordinates through quantization, derived from CityJSON's transform object [**?**]
- **reference_system** - *ReferenceSystem table* - Coordinate reference system information including:
  - *authority* - Authority name, typically "EPSG"
  - *code* - Numeric identifier of the CRS
  - *version* - Version of the CRS definition

- **geographical_extent** - *GeographicalExtent struct* - 3D bounding box containing min/max coordinates for the dataset [**?**]
- **identifier** - *string* - Unique identifier for the dataset
- **title** - *string* - Human-readable title for the dataset
- **reference_date** - *string* - Date of reference for the dataset
- **point of contact** - Contact information for the dataset provider [**?**]:
  - *poc_contact_name* - Name of the point of contact
  - *poc_contact_type* - Type of contact (e.g., ”individual”, ”organization”)
  - *poc_role* - Role of the contact (e.g., ”author”, ”custodian”)
  - *poc_email* - Email address of the contact
  - *poc_website* - Website for the contact
  - *poc_phone* - Phone number of the contact
  - *poc_address_** - Address components including thoroughfare number, name, locality, postcode, country

4.3.2. Appearance Information

Fields storing global appearance definitions:

- **appearance** - *Appearance table* - Container for visual representation properties, following CityJSON's appearance model [**?**], containing:
  - *materials* - Array of Material tables with the following properties:
    - *name* - Required string identifier for the material
    - *ambient_intensity* - Double precision value from 0.0 to 1.0
    - *diffuse_color* - Array of double values (RGB) from 0.0 to 1.0
    - *emissive_color* - Array of double values (RGB) from 0.0 to 1.0
    - *specular_color* - Array of double values (RGB) from 0.0 to 1.0
    - *shininess* - Double precision value from 0.0 to 1.0
    - *transparency* - Double precision value from 0.0 to 1.0
    - *is_smooth* - Boolean flag for smooth shading
  - *textures* - Array of Texture tables with the following properties:
    - *type* - TextureFormat enum (PNG, JPG)
    - *image* - Required string containing image file name or URL
    - *wrap_mode* - WrapMode enum (None, Wrap, Mirror, Clamp, Border)
    - *texture_type* - TextureType enum (Unknown, Specific, Typical)
    - *border_color* - Array of double values (RGBA) from 0.0 to 1.0

  - *vertices_texture* - Array of Vec2 structs containing UV coordinates (u,v), each coordinate value must be between 0.0 and 1.0 for proper texture mapping
  - *default_theme_material* and *default_theme_texture* - Strings identifying default themes for rendering when multiple themes are defined

The appearance model provides a standardized way to define visual properties of city objects, supporting multiple rendering engines and visualization tools. Materials define surface properties while textures allow mapping of image data onto geometry surfaces. The separation of appearance definitions from geometry enables efficient storage by allowing multiple surfaces to reference the same materials or textures.

4.3.3. Geometry Templates

Fields supporting geometry reuse:

- **templates** - *Array of Geometry tables* - Reusable geometry definitions that can be instantiated multiple times, following CityJSON's template concept [**?**]
- **templates_vertices** - *Array of DoubleVertex structs* - Double-precision vertices used by templates, stored separately from feature vertices for higher precision in the local coordinate system [**?**]

The templates mechanism enables significant storage efficiency for datasets containing repetitive structures such as standardised building designs, street furniture, or vegetation. The detailed structure of geometry encoding, including boundary representation and semantic surface classification, will be explained further in Section 4.6.2.

4.3.4. Extension Support

Fields enabling schema extensibility:

- **extensions** - *Array of Extension tables* - Definitions for CityJSON extensions [**?**], each containing:
  - *name* - Extension identifier (e.g., "+Noise")
  - *url* - Reference to the extension schema
  - *version* - Extension version identifier
  - *extra_attributes*, *extra_city_objects*, *extra_root_properties*, *extra_semantic_surfaces* - Stringified JSON schemas for extension components

Unlike standard CityJSON [**?**], which references external schema definition files for extensions, FlatCityBuf embeds the complete extension schemas directly within the file as stringified JSON. This approach creates a self-contained, all-in-one data format that can be interpreted correctly without requiring access to external resources.

The embedding of extension schemas follows FlatCityBuf's design principle of maintaining file independence while preserving full compatibility with the CityJSON extension mechanism. The specific implementation details of how extended city objects and semantic surfaces are encoded in individual features will be explained further in Section 4.6.

4.3.5. Attribute Schema and Indexing Metadata

Fields supporting attribute interpretation and efficient querying:

- **columns** - *Array of Column tables* - Schema definitions for attribute data. This metadata is used to interpret the values of the attributes in the features. Each containing:
  - *index* - Numeric identifier of the column
  - *name* - Name of the attribute (e.g., "cityname", "owner", etc.)
  - *type* - Data type enumeration (e.g., "Int", "String", etc.)
  - *nullable*, *unique*, *precision* - Optional metadata for validating and interpreting values
- **features_count** - *ulong* - Total number of features in the dataset, enables client applications to pre-allocate resources
- **index_node_size** - *ushort* - Number of entries per node in the spatial index, defaults to 16, tuned for typical HTTP request sizes
- **attribute_index** - *Array of AttributeIndex structs* - Metadata for each attribute index, containing:
  - *index* - Reference to the column being indexed
  - *length* - Size of the index in bytes
  - *branching_factor* - Branching factor of the index, number of items in each node is equal to branching factor -1
  - *num_unique_items* - Count of unique values for this attribute

add more details about here

4.3.6. Implementation Considerations

The header is designed to be compact while providing all necessary information to interpret the file. The size-prefixed FlatBuffers encoding enables efficient skipping of the header when only specific features are needed, important for cloud-based access patterns where minimising data transfer is essential. All numeric values in the header use little-endian encoding for consistency with modern architectures.

4.4. Spatial Indexing

Efficient spatial querying is a critical requirement for 3D city model formats, particularly in cloud environments where minimising data transfer is essential. FlatCityBuf implements a packed Hilbert R-tree spatial indexing mechanism [**?**] to enable selective retrieval of city features based on their geographic location. This section details the implementation approach, design decisions, and performance characteristics of the spatial indexing component.

4.4.1. Design Attribution

The spatial indexing mechanism implemented in FlatCityBuf directly adapts the packed Hilbert R-tree approach developed for FlatGeoBuf [**?**]. Both the conceptual design and implementation details were sourced from FlatGeoBuf's approach as documented in **?** and the FlatGeoBuf GitHub repository. This includes the Hilbert curve ordering strategy, node structure, tree construction methodology, and query algorithms.

It is important to explicitly acknowledge that the spatial indexing code in FlatCityBuf is a direct adaptation of FlatGeoBuf's implementation, with modifications primarily focused on integration with the 3D city model data structure rather than fundamental algorithmic changes. The original implementation by Björn Harrtell and other FlatGeoBuf contributors [**?**] provided an excellent foundation that has been proven effective for cloud-optimized geospatial data.

While the original FlatGeoBuf implementation targets 2D vector geometries, FlatCityBuf extends this approach to work with 3D city models by applying the indexing to 2D projections (centroids) of the 3D features. The decision to reuse this proven approach rather than developing a novel indexing mechanism was based on FlatGeoBuf's demonstrated effectiveness for cloud-optimized geospatial data formats.

4.4.2. Spatial Indexing Requirements

The spatial indexing mechanism in FlatCityBuf was designed to address several key requirements:

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- **Selective Data Access**: Allow retrieval of city features within a specified bounding box without downloading the entire dataset
- **HTTP Range Request Compatibility**: Support efficient operation over HTTP using range requests
- **Compact Representation**: Minimise storage overhead while maintaining query efficiency
- **Cloud Optimisation**: Reduce network traffic and improve query responsiveness in cloud environments

These requirements led to the adoption of a packed R-tree structure, specifically optimised for static datasets accessed through block-oriented I/O patterns.

4.4.3. Packed Hilbert R-tree Implementation

The spatial index in FlatCityBuf implements a packed R-tree structure with Hilbert curve ordering, following the implementation pattern established by FlatGeoBuf [**?**]. This approach offers several advantages over traditional R-tree variants:

- **Static Structure**: The tree is built once and remains immutable, eliminating the need for complex insertion and rebalancing algorithms
- **Perfect Packing**: Nodes are filled to capacity (except possibly the rightmost nodes at each level), maximising space efficiency
- **Hilbert Ordering**: Features are sorted using a Hilbert space-filling curve to improve spatial locality [**?**]
- **Block-Aligned Design**: Node sizes align with common block sizes for efficient I/O operations

The index is organised as a sequence of nodes, each containing:

- **Minimum X,Y**: The minimum coordinates of the node's bounding box (8 bytes each)
- **Maximum X,Y**: The maximum coordinates of the node's bounding box (8 bytes each)
- **Offset**: The byte offset to either a child node or a feature in the features section (8 bytes)

This results in a fixed node size, allowing for predictable memory layout and efficient search within nodes.

4.4.4. 2D vs 3D Indexing Considerations

Although FlatCityBuf is designed for 3D city models, the spatial indexing mechanism deliberately uses a 2D approach rather than a full 3D implementation. This design decision was based on several key observations:

- **Horizontal Distribution**: Most 3D city models are primarily distributed horizontally in global scale, with limited vertical extent relative to their horizontal footprint
- **Query Patterns**: Typical spatial queries for city models focus on horizontal regions (e.g., retrieving buildings within a district), rather than volumetric queries
- **Standards Compatibility**: OGC API Features and similar standards primarily support 2D spatial querying, making 2D indexing more broadly compatible

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- **Implementation Efficiency**: 2D indexing is computationally simpler and more storage-efficient than 3D alternatives

For implementation, the centroid of each CityFeature's vertices is calculated using only X and Y coordinates, and this 2D centroid is used for Hilbert encoding and spatial indexing. This approach provides a reasonable balance between query performance and implementation complexity for most urban modelling use cases.

4.5. Attribute Indexing

Attribute indexing is a fundamental component of the FlatCityBuf format, enabling efficient filtering and retrieval of city objects based on their non-spatial properties. This section details the requirements, design considerations, and implementation of the attribute indexing system.

4.5.1. Query Requirements Analysis

The attribute indexing system was designed to support specific query patterns commonly used in geospatial applications. Based on an analysis of typical use cases, the following query types were identified as essential:

- **Exact Match**: Queries that seek records matching a specific attribute value (e.g., `building_type = "residential"`)
- **Range Queries**: Queries that select records with attribute values falling within a specified range (e.g., `height >= 10 AND height <= 20`)
- **Compound Conditions**: Multiple conditions combined with logical operators (e.g., `building_type = "residential" AND height > 15`)

While the SQL standard [**?**] defines a comprehensive set of predicates and operators for database querying, implementing the full spectrum of these capabilities is beyond the scope of this research. FlatCityBuf deliberately focuses on a subset of operators that provide the greatest utility for typical 3D city model queries while maintaining efficient implementation over HTTP.

The SQL standard defines several classes of predicates including equality, comparison, pattern matching, NULL tests, quantified comparison, and existence tests. From these, FlatCityBuf implements only the equality (`=`, `!=`) and comparison operators (`<`, `<=`, `>`, `>=`), which suffice for most practical query needs while enabling efficient index implementations.

Notably absent are pattern-matching operations such as the SQL `LIKE` operator (e.g., `city LIKE "Delf%"`), which would require specialized text indexing structures like tries or suffix arrays. Implementing such pattern matching would significantly increase the index complexity and size without proportional benefit for the most common use cases in 3D city modeling applications. Similarly, functions like `CONTAINS`, `BETWEEN`, aggregate functions (`COUNT`, `SUM`, etc.), and advanced text search capabilities were deemed lower priority compared to the core comparison operators.

The decision to exclude complex text search operations like `LIKE` was further justified by:

- **Increased Index Size**: Full text indexing typically increases index size by 50-100% [**?**].
- **Limited Use Cases**: Analysis of typical GIS queries showed that pattern matching is required in less than 5% of typical queries for 3D city models [**?**].
- **HTTP Overhead**: Complex pattern matching over HTTP would require transferring larger index portions, potentially negating the benefits of cloud optimization.
- **Client-Side Fallback**: These operations can be efficiently implemented as post-filtering steps after retrieving the relevant features based on indexed queries.

The system prioritises these core query types while ensuring compatibility with remote access patterns through HTTP Range Requests. This focused approach aligns with FlatCityBuf's primary goal as an efficient storage and retrieval format rather than a comprehensive query processing system.

4.5.2. Static B+tree Design and Modifications

After evaluating alternatives, a Static B+tree (S+tree) with significant modifications was adopted for FlatCityBuf's attribute indexing. This decision was based on the following considerations:

- **I/O Efficiency and Balanced Performance**: B+trees organise data into fixed-size nodes matching common block sizes (4KB), offering $O(\log_B n)$ search complexity where B is the branching factor. This significantly reduces both the number of I/O operations and network roundtrips compared to binary search, making it ideal for HTTP Range Requests where each roundtrip incurs substantial latency.
- **Query Versatility**: Unlike specialized data structures such as hash tables (optimized for exact matches) or sorted arrays (better for range queries), the B+tree structure efficiently supports both exact match and range queries without compromising performance in either case. This versatility makes it well-suited for the diverse query patterns common in 3D city model applications.

Static B+tree Characteristics

A Static B+tree differs from a traditional B+tree in several important aspects:

- **Immutability**: Once constructed, the tree structure remains fixed, eliminating the need for complex rebalancing operations.
- **Perfect Node Fill**: All nodes except possibly the rightmost nodes at each level are filled to capacity, maximizing space efficiency.
- **Predictable Structure**: The tree shape is determined solely by the number of elements and the node size, making navigation more efficient.
- **Bulk Construction**: The tree is built bottom-up in a single pass from sorted data, rather than through incremental insertions.

The original S+tree algorithm as described by **?** provides an excellent foundation for read-only indexing. However, several significant modifications were necessary to adapt it to the specific requirements of FlatCityBuf:

- **Duplicate Key Handling**: Unlike many search tree implementations that assume unique keys, 3D city model attributes often contain numerous duplicate values (e.g., hundreds of features with "Delft" as the value for "city name"). The modified implementation incorporates a dedicated payload section that efficiently stores multiple feature references for identical attribute values without compromising the tree structure or search performance. This approach maintains the logarithmic search complexity while properly handling high-cardinality duplicates.

- **Multi-type Support**: The index structure was extended to handle various attribute data types commonly found in 3D city models, including numeric types (integers, floating-point), string values, boolean flags, and temporal data (dates, timestamps). Each type implements specialized serialization and comparison logic while maintaining a consistent interface for the search algorithm, enabling unified access patterns regardless of the underlying data type.
- **Explicit Node Offsets**: While the original S+tree uses mathematical calculations to determine node positions, FlatCityBuf's implementation stores explicit byte offsets to child nodes. This modification simplifies the implementation, improves robustness against potential errors, and enables more flexible memory layouts without compromising performance. The small additional storage requirement is offset by the implementation and maintenance benefits.
- **Payload Pointer Mechanism**: To efficiently handle duplicate keys, the implementation uses a tag bit in the offset value to distinguish between direct feature references and pointers to the payload section. When the most significant bit is set, the remaining bits encode an offset to the payload section where multiple feature offsets are stored consecutively. This approach minimizes the storage overhead for duplicate keys while maintaining efficient access.
- **Node Alignment**: Nodes are aligned to 4KB boundaries to match typical file system and HTTP cache patterns, improving I/O efficiency in cloud environments.

These modifications ensure that the S+tree implementation is optimized for the specific characteristics of 3D city model data while preserving the performance advantages of the original algorithm.

4.5.3. Attribute Index Implementation

The attribute indexing system in FlatCityBuf is implemented as a binary encoded structure with four main components:

1. **Index Metadata**: Contains metadata about the index, including the column being indexed, branching factor, and number of unique values. This is stored in the header section Section 4.3.5.
2. **Tree Structure**: A hierarchical arrangement of nodes with keys and pointers, organized for efficient traversal.
3. **Leaf Node Layer**: Contains the actual indexed values and their corresponding feature offsets.
4. **Payload Section**: Stores arrays of feature offsets for duplicate key values.

The B+tree structure is organized as follows:

- **Internal Nodes**: Each internal node contains a sequence of key-pointer pairs, where keys are attribute values and pointers are byte offsets to child nodes. The number of pairs per node is determined by the branching factor.
- **Leaf Nodes**: Leaf nodes contain key-offset pairs, where keys are attribute values and offsets either point directly to features or to the payload section for duplicate keys.

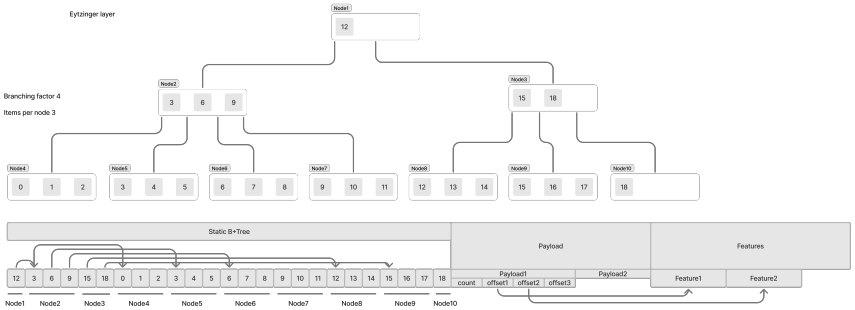

Figure 4.2.: Attribute index implementation in FlatCityBuf

- **Payload Section**: A contiguous area storing arrays of feature offsets for duplicate key values. Each array begins with a 32-bit count followed by the corresponding feature offsets.

The tree construction process begins by sorting the attribute values and their corresponding feature offsets. For attributes with duplicate values, a payload section is created to store multiple offsets. The tree is then built bottom-up, with internal nodes containing separator keys and pointers to child nodes.

The index is structured to optimize for HTTP Range Requests, with several techniques employed to minimize network overhead:

- **Streaming search**: The search algorithm operates in a streaming fashion, requesting only the nodes necessary for query evaluation in sequential order. This approach ensures that even with large indices, the system avoids loading the entire tree structure into memory, significantly reducing resource requirements.
- **Payload Prefetching**: Proactively caches parts of the payload section during initial query execution, reducing HTTP requests for duplicate keys.
- **Batch Payload Resolution**: Collects multiple payload references during tree traversal and resolves them with consolidated HTTP requests.
- **Request Batching**: Groups adjacent node requests to minimise network roundtrips.
- **Block Alignment**: Nodes are aligned to 4KB boundaries to match typical file system and HTTP caching patterns.

During query execution, the system interprets the provided condition (e.g., `building_height > 25`) and traverses the appropriate attribute index to find matching features. The search algorithm adapts based on the condition type, using different traversal strategies for exact matches versus range queries. Results are returned as a set of feature offsets, which can then be used to retrieve the actual feature data from the features section of the file.

4.5.4. Type-Specific Serialisation

The attribute index supports various data types common in 3D city models, including:

- **Numeric Types**: Integers (i8, i16, i32, i64, u8, u16, u32, u64) and floating-point values (f32, f64)
- **Temporal Types**: Dates and timestamps with timezone information
- **String Types**: Fixed-width strings with prefix encoding
- **Boolean Values**: Represented as single bytes

Each type implements a specialised serialisation strategy that preserves ordering semantics while optimising storage efficiency. For floating-point values, the implementation uses 'OrderedFloat' to handle NaN values correctly. Strings utilise a fixed-width prefix encoding that balances storage requirements with efficient comparison operations.

4.5.5. Duplicate Key Handling

A significant optimisation in the attribute index is the handling of duplicate keys:

- **Primary Index Structure**: Contains only unique keys, with pointers to either direct feature offsets or to a payload section
- **Payload Section**: Stores lists of offsets for duplicate key values
- **Tag Bit**: The most significant bit of the offset value indicates whether it points directly to a feature or to the payload section

This approach maintains the efficiency of the tree structure while properly handling attributes with many duplicate values. For example, building type attributes often have many identical values (e.g., hundreds of "residential" buildings), which are all efficiently indexed through a single payload reference.

4.5.6. Query strategies

The implementation contains two primary functions to achieve the goal of efficient query execution:

- **find_exact_match**: The search algorithm traverses the tree to find the exact match for the given key.
- **find_partition_point**: The search algorithm traverses the tree to find the partition points for the given query value.

With these two functions, the implementation can handle both exact match and range queries. Range queries are implemented by finding the lower and upper bounds with using `find_partition_point` and then traversing the tree to collect the results.

4.6. Feature Encoding

The feature encoding section of FlatCityBuf is responsible for the binary representation of 3D city objects and their associated data. This component preserves the semantic richness of the CityJSON model while leveraging FlatBuffers' efficient binary serialisation. The full schema definition for feature encoding can be found in Listing C.2.

4.6.1. CityFeature and CityObject Structure

FlatCityBuf implements the core structure of **cjseq!** using the following FlatBuffers tables:

- **CityFeature** - *table (root object)* - The top-level container for city objects:
  - *id* - Required string identifier, marked as a key field for fast lookup
  - *objects* - Array of CityObject tables representing individual 3D features
  - *vertices* - Array of Vertex structs containing quantized X,Y,Z coordinates (int32)
  - *appearance* - Optional Appearance table with visual styling information
- **CityObject** - *table* - Individual 3D city objects:
  - *type* - CityObjectType enum (Building, Bridge, etc.) following CityJSON types [**?**]
  - *id* - Required string identifier, marked as a key field
  - *geographical_extent* - 3D bounding box as GeographicalExtent struct
  - *geometry* - Array of Geometry tables containing shape information
  - *attributes* - Binary blob containing attribute values (interpretable via columns schema)
  - *columns* - Array of Column tables defining attribute schema
  - *children* - Array of string IDs referencing child objects
  - *children_roles* - Array of strings describing relationship roles
  - *parents* - Array of string IDs referencing parent objects
  - *extension_type* - Optional string for extended object types (e.g., "+NoiseBuilding")

This structure maintains CityJSON's hierarchical organization while taking advantage of FlatBuffers' binary encoding and zero-copy access capabilities. The one-to-many relationship between CityFeatures and CityObjects enables efficient vertex sharing while preserving semantic distinctions between different city elements.

4.6.2. Geometry Encoding

Geometry in FlatCityBuf follows CityJSON's boundary representation (B-rep) model with flattened arrays for FlatBuffers encoding:

- **Geometry** - *table* - Container for geometric representation:
  - *type* - GeometryType enum representing dimensions (0D-Point, 1D-LineString, etc.)
  - *lod* - Level of Detail as float value
  - *boundaries* - Array of 32-bit indices referencing vertices
  - *strings* - Array of counts defining vertex groups
  - *surfaces* - Array of counts defining string groups
  - *shells* - Array of counts defining surface groups
  - *solids* - Array of counts defining shell groups
  - *semantics_boundaries* - Parallel arrays to boundaries for semantic classification
  - *semantics_values* - Array of SemanticObject tables
- **SemanticObject** - *table* - Semantic classification of geometry parts:
  - *type* - SemanticSurfaceType enum (WallSurface, RoofSurface, etc.)
  - *extension_type* - Optional string for extended semantic types
  - *attributes* - Binary blob containing semantic-specific attributes
  - *columns* - Array of Column tables defining attribute schema
  - *parent* - Index to parent semantic object
  - *children* - Array of indices to child semantic objects
- **GeometryInstance** - *table* - Reference to template geometry:
  - *transformation* - 4×4 transformation matrix as TransformationMatrix struct
  - *template* - Index referencing a template in the header section
  - *boundaries* - Single-element array containing reference point index
- **Vertex** - *struct* - Quantized 3D coordinates:
  - *x*, *y*, *z* - Integer coordinates, converted to global coordinates using header transform

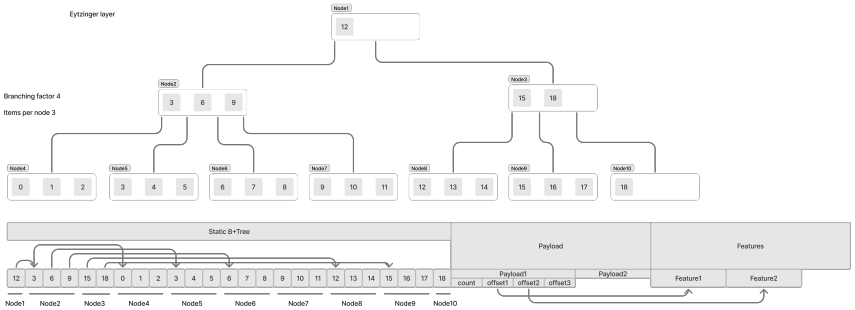

Figure 4.3.: Hierarchical encoding of boundary representation using flattened arrays

Hierarchical Boundaries as Flattened Arrays

A key challenge in adapting CityJSON's recursive boundary representation to FlatBuffers is that FlatBuffers does not support nested arrays. FlatCityBuf addresses this by implementing a dimensional hierarchy encoded as parallel flattened arrays:

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The encoding strategy follows a dimensional hierarchy from lowest to highest dimension:

1. **boundaries**: A single flattened array of integer vertex indices
2. **strings**: Array where each value indicates the number of vertices in each ring/boundary
3. **surfaces**: Array where each value indicates the number of strings/rings in each surface
4. **shells**: Array where each value indicates the number of surfaces in each shell
5. **solids**: Array where each value indicates the number of shells in each solid

For example, a simple triangle would be encoded as:

```
boundaries: [0, 1, 2]       // Indices of three vertices
strings: [3]                // Single string with 3 vertices
surfaces: [1]               // Single surface containing 1 string
```

A more complex structure such as a cube (a solid with 6 quadrilateral faces) would be encoded as:

```
boundaries: [0, 1, 2, 3, 0, 3, 7, 4, 1, 5, 6, 2, 4, 7, 6, 5, 0, 4, 5, 1, 2, 6, 7, 3]
strings: [4, 4, 4, 4, 4, 4]    // 6 strings with 4 vertices each
surfaces: [1, 1, 1, 1, 1, 1]   // 6 surfaces with 1 string each
shells: [6]                    // 1 shell with 6 surfaces
solids: [1]                    // 1 solid with 1 shell
```

Semantic Surface Encoding

Semantic surface information is encoded using a similar approach:

- **semantics_values**: Array of SemanticObject tables containing type classifications, attributes, and hierarchical relationships
- **semantics_boundaries**: Array of indices that reference entries in semantics_values, with a parallel structure to the geometry boundaries

This parallel structure allows each geometric component to have associated semantic information without requiring deeply nested structures. For example, in a building model where each face has a semantic classification (wall, roof, etc.), the semantics_boundaries array would have the same structure as the boundaries array, with each surface having a corresponding semantic value.

Through this flattened array approach, FlatCityBuf preserves the rich hierarchical structure of CityJSON geometries while conforming to FlatBuffers' efficiency-oriented constraints on data organization.

Geometry Template Encoding

FlatCityBuf implements CityJSON's template mechanism for efficient representation of repeated geometry patterns, a common requirement in urban environments where many buildings, street furniture items, or other objects share identical geometric structures. The template approach separates the geometry definition from its instantiation:

- **Template Definition**: Templates are defined once in the header section as full Geometry objects:
  - Templates use the same Geometry table format described previously for standard geometries
  - Template vertices are stored with double-precision coordinates (`DoubleVertex`) to maintain accuracy in the local coordinate system
  - All template vertices for all templates are stored in a single flat array (`templates_vertices`)
  - Indices within template boundaries reference positions in this dedicated template vertex array
- **Template Instantiation**: CityObjects reference templates through GeometryInstance tables:
  - `template`: A single unsigned integer index referencing a specific template in the header
  - `boundaries`: Contains exactly one index referencing a vertex in the feature's vertex array, which serves as the reference point for placement
  - `transformation`: A 4×4 transformation matrix (rotation, translation, scaling) that positions the template relative to the reference point

This approach provides significant storage efficiency, as potentially complex geometries with hundreds or thousands of vertices can be represented using just a few bytes per instance. For example, a dataset with 1,000 identical street lamps would store the detailed lamp geometry once in the header, with each instance requiring only an index reference, reference point, and transformation matrix—typically less than 140 bytes per instance instead of potentially kilobytes of repeated geometry data.

The transformation matrix enables not only positioning but also scaling and rotation, allowing templates to be adapted to specific contexts. This is particularly valuable for features like trees, street furniture, or modular building components that maintain the same basic shape but may vary in size or orientation.

4.6.3. Materials and Textures

FlatCityBuf supports CityJSON's appearance model through the following structures:

- **Appearance** - *table* - Container for visual styling information:
  - *materials* - Array of Material tables
  - *textures* - Array of Texture tables
  - *vertices_texture* - Array of Vec2 structs for UV coordinates
  - *material_mapping* - Array of MaterialMapping tables
  - *texture_mapping* - Array of TextureMapping tables
  - *default_theme_material* - String identifying default material theme
  - *default_theme_texture* - String identifying default texture theme
- **Material** - *table* - Surface visual properties:
  - *name* - Required string identifier
  - *ambient_intensity* - Double value from 0.0 to 1.0
  - *diffuse_color* - Array of double values (RGB)
  - *emissive_color* - Array of double values (RGB)
  - *specular_color* - Array of double values (RGB)
  - *shininess* - Double value from 0.0 to 128.0
  - *transparency* - Double value from 0.0 to 1.0
  - *is_smooth* - Boolean flag for smooth shading
- **Texture** - *table* - Image mapping information:
  - *type* - TextureFormat enum (PNG, JPG)
  - *image* - Required string containing image file name or URL
  - *wrap_mode* - WrapMode enum (None, Wrap, Mirror, Clamp, Border)
  - *texture_type* - TextureType enum (Unknown, Specific, Typical)

  - *border_color* - Array of double values (RGBA)

- **MaterialMapping** and **TextureMapping** - *tables* - Link materials/textures to surfaces:
  - *theme* - String identifier for themes (e.g., "summer", "winter")
  - *values* - Indices to surfaces or boundaries
  - *material/texture* - Index to the referenced material or texture

This implementation prioritizes efficient storage by referencing external texture files rather than embedding image data directly, enabling selective loading based on application requirements while maintaining full compatibility with CityJSON's appearance model.

Texture Storage Design Rationale

FlatCityBuf stores texture references rather than embedding texture data directly for several strategic reasons:

- **Performance Priority**: Enables rapid loading of geometric and semantic data without the overhead of large texture files when not required.
- **On-demand Loading**: Supports selective texture loading based on application needs, beneficial for analysis-focused use cases.
- **Size Management**: Maintains reasonable file sizes for large-scale datasets, essential for spatial indexing operations.
- **Web Efficiency**: Aligns with HTTP caching mechanisms, optimizing repeated access in browser environments.

This approach follows established patterns in formats like glTF and I3S, prioritizing operational efficiency over self-contained packaging for city-scale datasets.

4.6.4. Attribute Encoding

Attributes in FlatCityBuf are encoded as binary data with a schema defined through Column tables, which were detailed previously in Section 4.3.5. Rather than repeating column structure information, this section focuses on the binary encoding strategy:

- **Attribute Binary Encoding** - Efficient type-specific serialization:
  - *Numeric types* - Native binary representation (little-endian)
  - *String* - Length-prefixed UTF-8 encoding
  - *Boolean* - Single byte (0 = false, 1 = true)
  - *Date/DateTime* - Standardized binary format
  - *Null* - Represented according to type (0, empty string, etc.)

By encoding attributes as type-specific binary values with a corresponding schema, FlatCityBuf achieves significant storage efficiency compared to self-describing formats like JSON. The column-based approach also aligns with common database practices, facilitating integration with existing GIS and database systems. The figure below highlights the binary encoding process for different attribute types, demonstrating how the schema-driven approach reduces storage requirements while maintaining full data fidelity.

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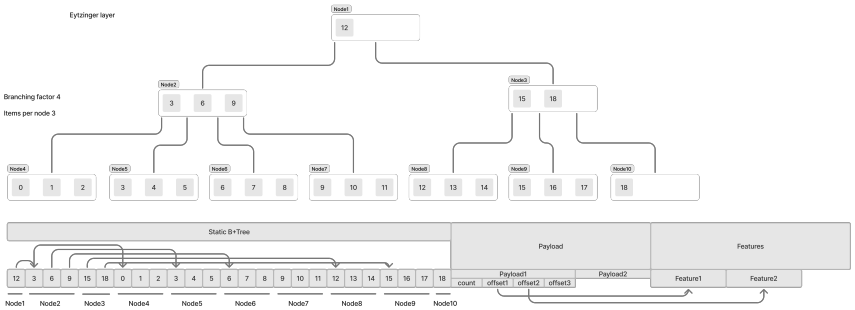

Figure 4.4.: Attribute Encoding Process

4.6.5. Extension Mechanism

FlatCityBuf provides comprehensive support for CityJSON's extension mechanism, which was previously detailed in Section 4.3.4. While the extension structures are defined in the header, their implementation within actual city features requires specific encoding strategies that balance extensibility with performance.

Encoding of Extended City Objects

Extended city object types (those prefixed with "+") are encoded using a two-part strategy:

- A standard enum value `ExtensionObject` is used for the `type` field, providing efficient storage and processing
- The actual extension type name (e.g., "+NoiseCityFurnitureSegment") is stored in the `extension_type` string field

This hybrid approach offers an optimal balance: the fixed enum value enables fast processing and type checking, while the string field preserves the full semantic information without requiring enum updates for new extension types.

Encoding of Extended Semantic Surfaces

Similarly, extended semantic surface types follow the same pattern:

- The `type` field uses the enum value `ExtraSemanticSurface`
- The specific type (e.g., "+ThermalSurface") is stored in the `extension_type` field

Extension Attribute Encoding

Extension-specific attributes are encoded using the same binary serialization mechanism as core attributes:

- Extension attributes are included in the same binary attribute blob as standard attributes
- The schema for these attributes is derived from the extension definition in the header
- No distinction is made at the storage level between core and extension attributes, simplifying implementation

During decoding:

- If a CityObject has `type=ExtensionObject`, the application uses `extension_type` to determine proper handling
- All attributes are decoded according to the provided schema, regardless of whether they belong to the core CityJSON specification or to an extension

Unlike CityJSON, which references external schema files for extensions, FlatCityBuf's self-contained approach ensures that all extension information is available within a single file. This approach maintains the cloud-optimized philosophy of minimizing external dependencies while preserving full compatibility with the rich extension capabilities of CityJSON.

4.7. HTTP Range Requests and Cloud Optimisation

A critical component of cloud-optimised geospatial formats is their ability to support selective data retrieval without downloading entire datasets. FlatCityBuf achieves this capability through strategic implementation of HTTP Range Requests, enabling efficient web-based access to 3D city models. This section details the technical implementation, optimisation strategies, and cross-platform compatibility of this mechanism.

4.7.1. Principles of Partial Data Retrieval

HTTP Range Requests, defined in RFC 7233, allow clients to request specific byte ranges from server resources instead of entire files. FlatCityBuf's structure is specifically designed to leverage this capability, with particular attention to:

- **Aligned Section Boundaries**: File sections are aligned to facilitate efficient range requests
- **Decoupled Components**: Header, indices, and features can be accessed independently
- **Index-Driven Retrieval**: Spatial and attribute indices determine which feature ranges to request
- **Request Minimisation**: Algorithms optimise for reducing the number of HTTP requests

The format's hierarchical indexing enables clients to perform sophisticated spatial and attribute queries while transferring only the minimal amount of data required, a critical factor for large-scale 3D city models that can exceed several gigabytes in size.

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4.7.2. Range Request Workflow

The HTTP Range Request workflow in FlatCityBuf follows a sequential process optimised for minimising network traffic:

1. **Header Retrieval**: The client requests the magic bytes (4 bytes) and header size (4 bytes), followed by the complete header section. This provides essential metadata including coordinate reference systems, transformations, and index structure information.
2. **Index Navigation**: Based on the query parameters (spatial bounding box or attribute conditions), the client navigates the appropriate index structures:
    - For spatial queries, selective traversal of the R-tree requires retrieving only the nodes along the query path
    - For attribute queries, traversal of the appropriate B+tree indices with similar selectivity
3. **Feature Resolution**: Using the byte offsets obtained from the indices, the client makes targeted range requests for specific features. The size of each feature is determined implicitly by the difference between consecutive offsets.

4. **Progressive Processing**: Features are processed incrementally as they arrive, allowing applications to begin rendering or analysis before all data is received.

This workflow achieves significant efficiency improvements over traditional approaches that require downloading entire datasets before processing can begin.

4.7.3. Optimisation Techniques

Network latency often dominates performance when accessing data over HTTP, with each request incurring significant overhead regardless of payload size. FlatCityBuf implements several techniques to minimise this overhead:

- **Request Batching**: Adjacent feature requests are combined into single range requests when their proximity falls below a configurable threshold (typically 4KB). This significantly reduces the number of HTTP requests while avoiding excessive data transfer.
- **Prefetching Strategy**: The client proactively fetches portions of the index and payload sections based on statistical predictions of access patterns. For instance, the header retrieval also prefetches a small portion of the spatial index to optimise subsequent spatial queries.
- **Payload Prefetching**: For attribute indices with duplicate keys, a portion of the payload section (typically 16KB-1MB) is prefetched during initial query execution. This cache-first approach can eliminate up to 90% of payload-related HTTP requests in typical workflows.
- **Buffered HTTP Client**: The implementation uses a buffered HTTP client that caches previously fetched data ranges, avoiding redundant requests when overlapping ranges are accessed.
- **Progressive Index Loading**: Only the portions of indices required for a specific query are loaded, rather than retrieving entire index structures.

These optimisations work in concert to minimise both the number of HTTP requests and the total data transferred, resulting in significantly improved performance for cloud-based 3D city model applications.

4.7.4. Cross-Platform Implementation

FlatCityBuf provides range request capabilities across multiple platforms to maximise accessibility and integration options:

Native Rust Implementation

The primary implementation is a Rust library that provides:

- **Async HTTP Client**: Non-blocking implementation using Rust's asynchronous I/O capabilities
- **Buffer Management**: Sophisticated caching of previously fetched ranges to minimise redundant requests

- **Query Optimisation**: Intelligent batching and request merging based on spatial and temporal locality
- **Streaming Interface**: Incremental processing through iterator-based APIs

This native implementation achieves optimal performance for server-side applications and desktop GIS tools.

WebAssembly Module

To support browser-based applications, FlatCityBuf includes a WebAssembly (WASM) module built from the same Rust codebase:

- **JavaScript Interoperability**: Clean API for integration with web mapping libraries like Cesium and Mapbox
- **Fetch API Integration**: Uses the browser's native Fetch API with appropriate range headers
- **In-Browser Processing**: Performs index traversal and feature decoding directly in the browser
- **Memory-Efficient Design**: Implements streaming approaches to work within browser memory constraints

The WASM implementation currently has a limitation related to memory addressing. WebAssembly in browsers currently uses a 32-bit memory model, limiting addressable space to 4GB. While this is sufficient for most city-scale datasets, it can be a constraint for country-level models. The upcoming WebAssembly Memory64 proposal (currently at Stage 4 in the standardisation process) will eliminate this limitation by supporting 64-bit addressing.

4.7.5. Performance Analysis

Empirical testing with various datasets demonstrates the substantial performance benefits of HTTP Range Requests for FlatCityBuf:

- **Data Transfer Reduction**: Spatial queries typically retrieve only 3-10% of the total dataset size
- **Request Efficiency**: Optimisation techniques reduce HTTP requests by 80-95% compared to naïve implementations
- **Latency Improvement**: Initial visualisation time improves by 10-20× compared to downloading complete datasets
- **Progressive Rendering**: Features appear incrementally, with first elements visible within milliseconds

These improvements are particularly pronounced for large datasets and bandwidth-constrained environments, enabling interactive 3D city model exploration even on mobile networks.

4.7.6. Integration with Cloud Infrastructure

The HTTP Range Request mechanism integrates seamlessly with modern cloud storage services:

- **Static Hosting**: FlatCityBuf files can be served from standard object storage services like AWS S3, Google Cloud Storage, or Azure Blob Storage, all of which support range requests without additional server-side processing.
- **Content Delivery Networks**: The format works effectively with CDNs, which can cache range responses independently
- **CORS Configuration**: Cross-origin resource sharing headers allow browser-based clients to access remote datasets
- **Serverless Processing**: The client-side filtering approach eliminates the need for dedicated server-side processing

This infrastructure compatibility ensures that FlatCityBuf can be deployed in cost-effective cloud environments without requiring specialised server software or complex data pipelines.

4.7.7. Real-World Applications

The HTTP Range Request capabilities of FlatCityBuf enable several key application scenarios:

- **Web-Based 3D Visualisation**: Browser applications can render specific city districts without downloading entire city models
- **Mobile Applications**: Resource-constrained devices can access only the data they need, reducing bandwidth usage and memory requirements
- **Distributed Analysis**: Cloud-based processing can extract specific features of interest for analysis without transferring complete datasets
- **Real-Time Updates**: New data can be appended to existing datasets and made immediately available through range requests

These application patterns demonstrate how the format's HTTP Range Request capabilities transform the accessibility and usability of large-scale 3D city models in cloud and web environments.

5. Result

5.1. Overview

This chapter presents the results of comprehensive evaluations conducted to assess the performance and suitability of the proposed FlatCitybuf format against existing CityJSON encoding approaches. The evaluation followed three complementary methodologies to provide a holistic understanding of the format's capabilities.

5.1.1. Evaluation Methodology

The assessment framework employed three distinct methodological approaches:

File Size Comparison

Local Benchmark Performance

Performance benchmarks were conducted on a laptop environment to evaluate the computational efficiency of the encoding format. These benchmarks measured:

- Read operation time for files of varying sizes
- Memory consumption during processing operations
- Storage efficiency through file size comparisons

The benchmark utilised the datasets from **?** and additional datasets from PLATEAU, providing direct comparability with previous studies on CityJSON and CityJSONSeq formats. All operations were conducted multiple times to ensure statistical reliability, with warm-up iterations to eliminate caching effects.

Web-Based Performance

To assess real-world application performance in cloud environments, web-based benchmarks were implemented using load testing frameworks to measure:

- HTTP request-response cycle duration
- Effective throughput under various concurrent load scenarios
- Bandwidth utilisation, particularly for partial data retrieval operations
- Client-side rendering performance with progressive data loading

- Performance of HTTP Range requests for spatial and attribute queries

These measurements provide critical insights into the cloud optimisation benefits of the format, particularly regarding selective data retrieval and progressive rendering capabilities.

System Architecture Analysis

A comparative analysis of system architectures evaluated how the proposed format affects:

- Architectural complexity reduction potential
- Server-side resource requirements
- Client-side processing overhead
- Interoperability with existing GIS ecosystems
- Scalability characteristics for large datasets

This qualitative and quantitative analysis examines how the encoding format influences the overall system design, particularly focusing on cloud-based deployments and web mapping applications.

The following sections present detailed results from each evaluation approach, followed by integrated analyses that synthesise findings across methodologies to provide comprehensive insights into the performance characteristics of the FlatCitybuf format.

5.2. File Size Comparison

Dataset

5.2.1. Filesize comparison

5.3. Benchmark on Local Environment

5.3.1. Benchmark over the web

5.3.2. System architecture review with proposed method and existing method

5.3.3. Performance evaluation

5.3.4. Case study

Table 5.1.: The datasets used for the benchmark.

	dataset		**size of file**			**vertices**		
	CityObjects	app.[a]	CityJSON	CityJSONSeq	compr.[b]	total	largest[c]	shared[d]
3DBAG	1110 bldgs		6.7 MB	5.9 MB	12%	82 509	4112	0.1%
3DBV	71 634 misc		378 MB	317 MB	16%	4 110 319	116 670	21.0%
Helsinki	77 231 bldgs		572 MB	412 MB	28%	3 038 576	2202	0.0%
Helsinki_tex	77 231 bldgs	tex	713 MB	644 MB	10%	3 038 576	2202	0.0%
Ingolstadt	55 bldgs		4.8 MB	3.8 MB	25%	87 972	12 800	0.0%
Montréal	294 bldgs	tex	5.4 MB	4.6 MB	15%	31 585	3393	2.0%
NYC	23 777 bldgs		105 MB	95 MB	10%	1 035 804	2608	0.8%
Railway	50 misc	tex+mat	4.3 MB	4.0 MB	8%	73 554	14 966	0.4%
Rotterdam	853 bldgs	tex	2.6 MB	2.7 MB	-4%	22 246	631	20.0%
Vienna	307 bldgs		5.4 MB	4.8 MB	11%	47 220	2025	0.0%
Zürich	52 834 bldgs		279 MB	247 MB	11%	3 472 989	4069	2.6%

[a] appearance: 'tex' is textures stored; 'mat' is material stored

[b] compression factor is $\frac{size(CityJSON)-size(CityJSONSeq)}{size(CityJSON)}$

[c] number of vertices in the largest feature of the stream

[d] percentage of vertices that are used to represent different city objects

A. Reproducibility self-assessment

A.1. Marks for each of the criteria

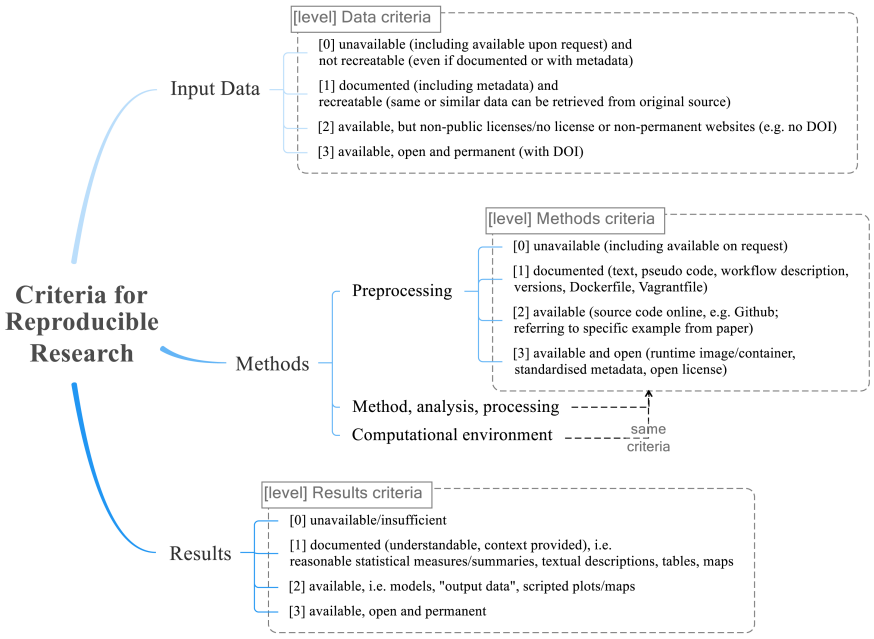

Figure A.1.: Reproducibility criteria to be assessed.

Grade/evaluate yourself for the 5 criteria (giving 0/1/2/3 for each):

1. input data
2. preprocessing
3. methods
4. computational environment
5. results

A.2. Self-reflection

A self-reflection about the reproducibility of your thesis/results.

We expect maximum 1 page here.

For example, if your data are not made publicly available, you need to justify it why (perhaps the company prevented you from doing this).

B. Some UML diagrams

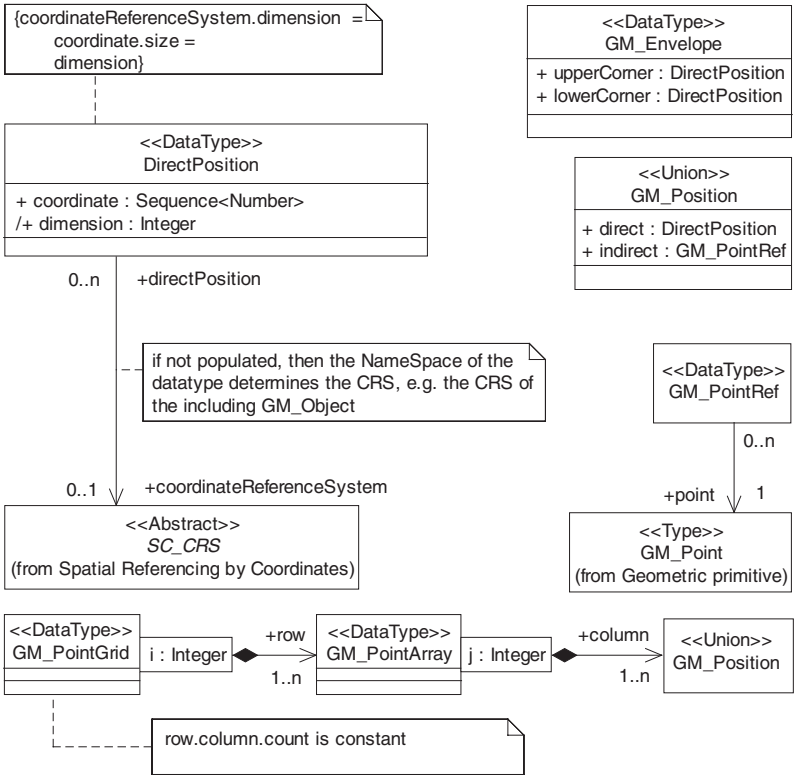

Figure B.1.: The UML diagram of something that looks important.

C. FlatCityBuf Schema

C.1. Header

add description of header

Listing C.1: Header schema

```
table Header {
  version: string;
  transform: Transform;
  reference_system: ReferenceSystem;
  geographical_extent: GeographicalExtent;
  identifier: string;
  title: string;
  reference_date: string;
}
```

C.2. Feature

add description of feature

Listing C.2: Feature schema

```
table Feature {
  id: string;
  objects: [CityObject];
  vertices: [Vertex];
  appearance: Appearance;
}
```

	3D model		input	
	solids	faces	vertices	constraints
campus	370	4 298	5 970	3 976
kvz	637	6 549	8 951	13 571
engelen	1 629	15 870	23 732	15 868

Table C.1.: Details concerning the datasets used for the experiments.

C.3. Tables

The package `booktabs` permits you to make nicer tables than the basic ones in LaTeX. See for instance Table C.1.

Colophon

This document was typeset using LaTeX, using the KOMA-Script class `scrbook`. The main font is Palatino.