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3D, temporal and documented cities : formalization, visualization and navigation

Vincent Jaillot

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Vincent Jaillot. 3D, temporal and documented cities: formalization, visualization and navigation. Computer Vision and Pattern Recognition [cs.CV]. Université de Lyon, 2020. English. NNT : 2020LYSE2026 . tel-03228436

HAL Id: tel-03228436

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N° d'ordre NNT : 2020LYSE2026

THESE de DOCTORAT DE L'UNIVERSITÉ DE LYON

Opérée au sein de

L'UNIVERSITÉ LUMIÈRE LYON 2

École Doctorale : ED 512 Informatique et Mathématiques

Discipline : Informatique

Soutenue publiquement le 10 septembre 2020, par :

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3D, temporal and documented cities : formalization, visualization and navigation

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3D, temporal and documented cities: formalization, visualization and navigation

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University of Lyon, University Lyon 2, LIRIS Laboratory, LabEx IMU
2020

A thesis presented for the degree of

Doctor of Computer Science

Doctoral school: ED 512 “Informatique et Mathématiques”



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Abstract

The study and understanding of cities evolution is an important societal issue, particularly for improving the quality of life in an increasingly dense city. Digital technology and in particular 3D city models can be part of the answer. Their manipulation is however sometimes complex due to their thematic, geometric, topological dimensions and hierarchical structure.

In this thesis, we focus on the integration of the temporal dimension and in the enrichment with multimedia documents of these 3D models of the city, in an objective of visualization and navigation on the web. Moreover, we take a particular interest in interoperability (based on standards), reusability (with a shared software architecture and open source components) and reproducibility (to make our experiments durable).

Our first contribution is a formalization of the temporal dimension of cities for interactive navigation and visualization on the web. For this, we propose a conceptual model of existing standards for the visualization of cities on the web, which we extend with a formalization of the temporal dimension. We also propose a logical model and a technical specification of these proposals.

Our second contribution allows the integration of multimedia documents into city models for spatial, temporal and thematic visualization and navigation on the web. We propose a conceptual model for the integration of heterogeneous and multidimensional geospatial data. We then use it for the integration of multimedia documents and 3D city models.

Finally, this thesis took place in a multidisciplinary context via the Fab-Pat project of the LabEx IMU, which focuses on cultural heritage sharing and shaping. In this framework, a contribution combining social sciences and computer science has allowed the design of DHAL, a methodology for the comparative analysis of devices for sharing heritage via digital technology.

Resumé

L'étude et la compréhension de l'évolution des villes est un enjeu sociétal important, notamment pour améliorer la qualité de vie dans une ville toujours plus dense. Le numérique et en particulier les modèles 3D de villes peuvent être des éléments de réponse. Leur manipulation est parfois rendue complexe par la prise en compte de leurs dimensions thématique, géométrique et topologique ainsi que de leur structuration hiérarchique.

Dans cette thèse, nous nous intéressons à l'intégration de la dimension temporelle et à l'enrichissement avec des documents multimédia de ces modèles 3D de la ville, dans un objectif de visualisation et de navigation sur le web. Nous portons un intérêt particulier à l'interopérabilité (en s'appuyant sur des standards), à la réutilisabilité (avec une architecture logicielle partagée et des composants open source) et à la reproductibilité (permettant de rendre nos expérimentations pérennes).

Notre première contribution est une formalisation de la dimension temporelle des villes pour une navigation et visualisation interactive sur le web. Pour cela, nous proposons un modèle conceptuel des standards existants pour la visualisation de villes sur le web, que nous étendons avec une formalisation de la dimension temporelle. Nous proposons également un modèle logique et une spécification technique de ces propositions.

Notre deuxième contribution permet d'intégrer des documents multimédias aux modèles de villes pour une visualisation et une navigation spatiale, temporelle et thématique sur le web. Nous proposons un modèle conceptuel pour l'intégration de données géospatiales hétérogènes et multidimensionnelles. Nous l'utilisons ensuite pour l'intégration de documents multimédias et de modèles 3D de villes.

Enfin, cette thèse s'est déroulée dans un contexte pluridisciplinaire via le projet Fab-Pat, du LabEx IMU, qui s'intéresse au partage de la fabrique du patrimoine. Dans ce cadre, une contribution mêlant sciences sociales et informatique a permis de concevoir DHAL, une méthodologie pour l'analyse comparative de dispositifs pour le partage du patrimoine via le numérique.

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Glossary

3D city model 3D city models are digital models of urban areas that represent terrain surfaces, sites, buildings, vegetation, infrastructure and landscape elements in three-dimensional scale as well as related objects (e.g., city furniture) belonging to urban areas. Their components are described and represented by corresponding two-dimensional and three-dimensional spatial data and georeferenced data. 3D city models support presentation, exploration, analysis, and management tasks in a large number of different application domains. In particular, 3D city models allow “for visually integrating heterogeneous geoinformation within a single framework and, therefore, create and manage complex urban information spaces.” Source: Wikipedia¹. 2–6, 8, 12, 104

city object Refer to types of features like buildings, parks, bridges, etc. composing the city, such as usually defined in common urban data models (INSPIRE [INS14], CityGML [Ope12], IFC [Int18], etc.). A city object is a geographic feature. 3, 5, 13, 61

cultural heritage “Cultural heritage is the legacy of physical artifacts and intangible attributes of a group or society that is inherited from past generations. Not all legacies of past generations are ‘heritage’, rather heritage is a product of selection by society.” Source: Wikipedia² based on [Log07]

Cultural heritage is commonly divided in two categories: intangible cultural heritage and tangible cultural heritage (e.g. by the UNESCO³ or in [Vec10]). According to the UNESCO, *tangible cultural heritage* refers to “movable cultural heritage (paintings, sculptures, coins, manuscripts), immovable cultural heritage (monuments, archaeological sites, and so on) and underwater cultural heritage (shipwrecks, underwater ruins and cities)”. Still according to the UNESCO, *Intangible cultural heritage* refers to “oral traditions, performing arts, rituals”. 3, 4

¹https://en.wikipedia.org/wiki/3D_city_models

²https://en.wikipedia.org/wiki/Cultural_heritage

³<http://www.unesco.org/new/en/culture/themes/illicit-trafficking-of-cultural-property/unesco-database-of-national-cultural-heritage-laws/frequently-asked-questions/definition-of-the-cultural-heritage/>

digital urban heritage tool We name digital urban heritage tools, digital tools that allow to represent and interact with urban heritage. They take various forms, going from databases to 3D virtual tours, and some include participatory functionality. 4, 8, 84–86, 89, 92, 97, 98

feature Abstraction of real world phenomena. Sources: [Int08] and OGC⁴. 4, 6, 7, 56, 57, 66, 104, 106

geographic feature Representation of real world phenomenon associated with a location relative to the Earth. Sources: [Int08] and OGC⁵. viii, 17, 34–36, 52

geometric object A combination of a coordinate geometry and a coordinate reference system. In general, a geometric object is a set of geometric points. Source: OGC⁶. 6

integration To form, coordinate, or blend into a functioning or unified whole. Source: <https://www.merriam-webster.com/dictionary/integrate>. 4, 5

interactive visualization The term *interactive visualization* is usually applied to systems that provide feedback to users within several seconds of input. Source: Wikipedia⁷

Note: We use the same definition for *interactive navigation* 5, 104

multimedia document Multimedia documents are digital documents in the form of text, graphic, image, video, audio, etc. Typical examples of documents are photographs, audio recordings, postal cards, newspaper articles, etc. 6, 8, 104

raster data In its simplest form, a raster consists of a matrix of cells (or pixels) organized into rows and columns (or a grid) where each cell contains a value representing information, such as temperature. Rasters are digital aerial photographs, imagery from satellites, digital pictures, or even scanned maps. Source: ArcGIS documentation⁸. 15

⁴<https://www.opengeospatial.org/ogc/glossary/f>

⁵<https://www.opengeospatial.org/ogc/glossary/g>

⁶<https://www.opengeospatial.org/ogc/glossary/g>

⁷https://en.wikipedia.org/wiki/Interactive_visualization

⁸<https://desktop.arcgis.com/en/arcmap/10.3/manage-data/raster-and-images/what-is-raster-data.htm>

vector data A representation of the world using points, lines, and polygons. These data are created by digitizing the base data. They store information in x, y coordinates. Source: Pitney bowes⁹. 15

⁹https://support.pitneybowes.com/SearchArticles/VFP05_KnowledgeWithSidebarHowTo?id=kA180000000Cu9DCAS&popup=false&lang=en_US

List of Publications

The following is a list of publications containing the work presented in this thesis:

International Journals:

Jaillot Vincent, Istasse Manon, Servigne Sylvie, Gesquière Gilles, Rautenberg Michel and Lefort Isabelle (2020). *Describing, comparing and analysing digital urban heritage tools: A methodology designed with a multidisciplinary approach*. Digital Applications in Archaeology and Cultural Heritage. <https://doi.org/10.1016/j.daach.2020.e00135>

Jaillot Vincent, Servigne Sylvie and Gesquière Gilles (2020). *Delivering time-evolving 3D city models for web visualization*. International Journal of Geographical Information Science.

International Conferences:

Jaillot Vincent, Pedrinis Frederic, Servigne Sylvie, and Gesquière Gilles (2017). *A generic approach for sunlight and shadow impact computation on large city models*. 25th International Conference on Computer Graphics, Visualization and Computer Vision 2017, May 29 – June 2, 2017, Pilsen (Czech Republic).

National Conferences:

Istasse Manon and **Jaillot Vincent** (2018). *FAB-PAT: un atlas numérique participatif et évolutif pour partager la fabrique du patrimoine*. Actes du colloque Le crowdsourcing pour partager, enrichir et publier des sources patrimoniales, October 19, 2017, Angers (France).

Introduction

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1.1 Context

Urban areas are changing and growing at various granularity levels in space and in time. Buildings are constructed, roofs are restored, districts are revamped, bridges are destructed, parks are created, etc. Throughout these modifications, cities undergo horizontal and vertical sprawls. Figure 1.1 shows the evolution of the cities of Seoul between 1900 and 2016 and of Abu Dhabi between 1970 and 2016¹. Current projections² predict that the number of people living in urban areas will increase from the current 55% to 68% in 2050. This increase will perpetuate the profound modifications undergone by cities. In this context, understanding the city, its evolution and how people live in it becomes a central issue.

Seoul, South Korea



Abu Dhabi, United Arab Emirates

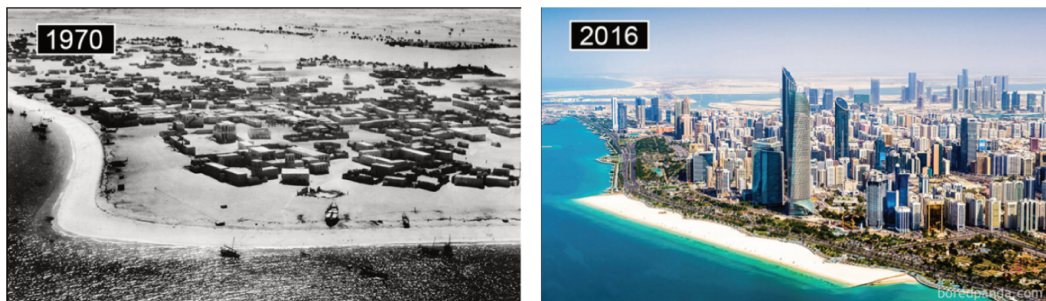


Figure 1.1.: Example of evolution of the cities of Seoul, South Korea and Abu Dhabi, United Arab Emirates with pictures taken at different dates. Images taken from: <https://www.boredpanda.com/how-famous-city-changed-timelapse-evolution-before-after>

3D city models³ provide digital representations of urban areas with 3D geometric, thematic and geo-referenced elements at different scales. These elements are

¹The scale and view points of the images are not exactly the same. However, these images still highlight the evolution these cities.

²<https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html>

³Asterisks indicate the first use of a word defined in the glossary.

commonly named *city objects** and they refer to buildings, trees, parks, bridges, tunnels, urban furniture etc. 3D city models have been widely used in the past years in research and industry, for many applications such as cultural heritage* preservation and sharing, energy demand analyses, noise mapping, environmental simulations, etc. [Dö+06; Bil+14; Bil+15].

With the development of web technologies and through their apparition in popular applications such as Google Maps⁴ (see figure 1.2), 3D city models also start to be used by non experts. While the 3D models used by Google have a detailed geometric dimension, they are not available and there is little information about their format, the spatial and temporal coverage, the thematic information associated with it, etc. However, several cities such as Lyon⁵, Berlin⁶ or New York⁷ give their 3D city models in open access and in standard formats, opening up possibilities for new methods and tools.

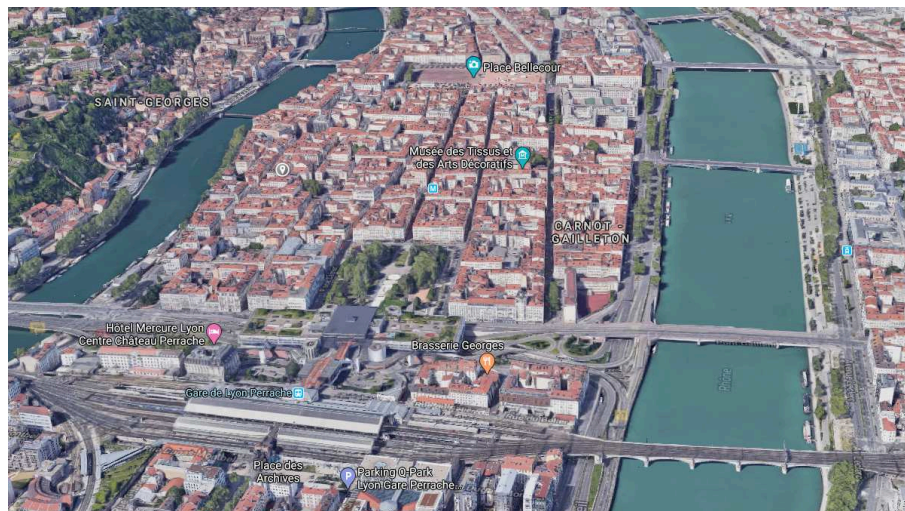


Figure 1.2.: Screenshot of the city of Lyon, France in the 3D mode of Google Maps.

The development history of a city is key to its understanding. Preserving and analyzing past and present cities and planning tomorrow's cities are essential to make appropriate decisions for the future. Data and tools representing cities evolution have many applications such as helping environmentalists to study cities energy balance evolution or urban planners to plan future evolution of the city. Moreover, it can help answering questions such as: *What is the lifecycle of a specific building ? Why did this road network structure evolved ? How an ordinary building may evolve*

⁴<https://www.google.com/maps>

⁵<https://data.grandlyon.com/jeux-de-donnees/maquettes-3d-texturees-a-commune-arrondissement-2009-2012-2015-metropole-lyon/info>

⁶<https://www.businesslocationcenter.de/en/economic-atlas/download-portal/>

⁷<https://www1.nyc.gov/site/doitt/initiatives/3d-building.page>

into a popular cultural heritage element ? etc. Managing the temporal dimension of cities is therefore essential.

3D city models alone are however not enough to understand the city and its evolution. Other features* from a variety of sources can provide complementary elements leading to more complete analyses of the city and hence to additional elements of comprehension of the city. Multimedia documents for instance are a key material for explaining the evolution of the city, for describing specific events that took place in the city, etc. Pictures, audio and video recordings, postal cards, journal articles, etc. bear numerous and valuable information. Gathering, sharing and exploiting documents contributes to preserving common knowledge. They describe cities, their evolution and how people live (in) it. Combined with the evolution of the city, they also help to answer questions such as *How was the city at a given time and how can we prove it ?* Furthermore, Münster et al. [Mü+20] emphasize that browsing multimedia documents in physical archives or in online repositories can be time-consuming and even counter-productive, especially given the number and diversity of available documents. They also highlight that using 3D interfaces and 3D city models may enhance multimedia documents *navigation* (i.e. access, querying), which highlights the need of 3D city models and multimedia documents integration*.

This thesis takes place in the *Fab-Pat* project⁸ funded by the LabEx IMU⁹ (Intelligences of Urban Worlds). *Fab-Pat* focuses on *urban cultural heritage sharing* and on involving citizens and associations in *urban heritage shaping*. This project gathers researchers in computer science (in the fields of data science and computer graphics with and expertise on geospatial data), in social sciences (in the fields of anthropology and geography with specific expertise on cultural heritage) and of experts from the cultural heritage department of the city of Lyon, France and from the Gadagne¹⁰ and Confluence¹¹ museums. In this context, an investigation of digital urban heritage tools* and interviews with actors of cultural heritage in the area of Lyon have been realized. They confirmed the need to provide new *visualization* and *navigation* possibilities for cultural heritage sharing. Many digital urban heritage tools indeed currently consist in geolocating multimedia documents on 2D maps. This is as much the case for small local associations (e.g. Sites and Cities association of Lyon¹²), as for established participative tools (e.g. PastPort¹³) as it is for institutional cultural

⁸<https://imu.universite-lyon.fr/bilan-2016/fabpat-sharing-the-shaping-of-heritage-approach-and-issues-concerning-the-historical-urban-landscape-hul-2016/>

⁹<https://imu.universite-lyon.fr/>

¹⁰[http://www.gadagne.musees.lyon.fr/index.php/gadagne/\(lang\)/en](http://www.gadagne.musees.lyon.fr/index.php/gadagne/(lang)/en)

¹¹<http://www.museedesconfluences.fr/fr/visit-museum>

¹²tool number 6 in the table of Appendix C

¹³tool number 3 in the table of Appendix C

heritage organization (e.g. the cultural heritage and general inventory department of the *Auvergne-Rhône-Alpes* region (France)¹⁴). While these initiatives share very interesting content, navigation possibilities may be enhanced and more information may be displayed with 3D city models integration.

1.2 Problem description

Based on this context and on Fab-Pat objectives, in this thesis, we focus on addressing the following research problem: **How to integrate the temporal dimension and multimedia documents to 3D city models for web visualization and navigation?** By visualization and navigation we intend offering functionality for users to query, access and display enhanced 3D city models information among space, time and thematic dimensions and with various interaction possibilities: by moving in space, by shifting time, by accessing multimedia documents from 3D city objects and 3D city objects from multimedia documents. This problem raises several challenges and leads to two research questions detailed in the following.

First, some challenges are related to **3D city models visualization and navigation**. These models can indeed represent hundreds of km^2 of data (which can correspond to millions of geometric primitives plus thematic information). In addition, we aim at achieving *interactive visualization* and navigation*, i.e. our system should provide response to users within several seconds. This challenge is well known in the computer graphics community. However, it is emphasized by the need of working in a *web context* and with 3D city models that not only comprise *3D geometry* (as it is the case for many computer graphics use cases) but also *structured thematic information* describing the objects and their relations (e.g. a building is composed of a roof, walls, doors, etc.).

Secondly, some challenges are specific to the **integration of the temporal dimension to 3D city models**. Changes in the city occur at various levels of granularity in space (e.g. roof restoration, construction of a new bridge, renovation of a district, etc.) and in time (renovation work of cultural heritage elements can take years while the construction of a house can take a few months). Therefore, we must propose a formalization allowing to represent changes at *various granularity levels* in space and in time. In addition, we take a particular interest in the *life-cycle* of city objects, which is essential for understanding cities evolution. Finally, we still want to keep the *navigation and visualization interactive*. This can be a big challenge since

¹⁴<https://patrimoine.auvergnerhonealpes.fr/>

adding the temporal dimension can greatly increase the number of city objects to manage and therefore the *datasets size*. This lead to the following research question: **How to formalize the temporal dimension of 3D city models for interactive web navigation and visualization of changes happening at various granularity levels ?**

Thirdly, **integrating multimedia documents to 3D city models** for web navigation and visualization raises other challenges. Features (including multimedia documents and 3D city models) are commonly described in one or more of the following three dimensions: thematic, geometric and temporal. The thematic dimension gives contextual information such as the nature of a feature or semantic metadata. The geometric dimension contains geometric objects* (e.g. points, polygons) that are defined in a coordinate reference system. Finally, the temporal dimension describes the diachronic nature of features. In addition, *multiple possibilities of navigation* have been identified and they can be classified in two types: querying features according to one (or more) of their dimensions and navigating from one (or more) features to one (or more) other associated features. In the first case, spatial queries are the most common case and they consists in accessing features at a given location or in a certain area. In the context of a 3D system, this may occur by moving in a virtual 3D environment and by accessing features that are in the field of view. Queries on geospatial features have been classified in eleven types by Yuan and McIntosh [YM02] : attribute queries, 3 spatial queries, 3 temporal queries and 4 spatio-temporal queries. For this type of navigation, features integration may be done by the querying system when presenting the result. The second type of navigation however, requires to associate features of different type together, based on specific criteria. Those criteria may for instance be thematic: a picture refers a building (pictures and building being two thematic entities). They can also be spatial, i.e. based on correspondence points between the picture and the building. These challenges lead to the following research question: **How to integrate multimedia documents* and 3D city models for visualization and navigation on the web ?** Note that in this thesis, we do not address potential issues raised by the management of large amounts of multimedia documents and that we focus on navigation and visualization.

Fourthly, this context also raises **technological challenges**. Designing an information system managing 3D geospatial information on the web is still a challenging task [Min08; Cha+15; PD16]. One of the major difficulty lies in the fact that the current context for 3D geospatial data management on the web is based on recent standards and tools which are evolving rapidly. For instance, the first standard dedicated to 3D cities modelling is CityGML [Kol09; Ope12] which has been introduced in 2008,

has undergone significant changes in 2012 in the version 2.0 and for which another version with major changes is planned in 2020. In the web context, first standards for managing large 3D geospatial data were only recently proposed: I3S [Ope17b] in 2017 and 3D Tiles [Ope19] in 2019. The technological environment around these standards is also emerging and unstable. For instance, there is currently no reference implementation provided along with the CityGML standard. Therefore, a current need and trend is the development of open-source and stable tools to manage data in these standards.

Finally, we aim at proposing scientific methods and software implementation that are **reproducible**, **reusable** and **interoperable**. Reproducibility refers to the ability to reproduce the results presented in this thesis. Reusability refers to proposing contributions (being scientific or software contributions) that can be reused by the scientific community. Interoperability refers to the possibility of our methods and implementation to interact with other systems. These objectives guided the scientific and software propositions of this thesis.

1.3 Contributions

First, we propose contributions addressing the first research question for **integrating the temporal dimension to 3D city models** for interactive web navigation and visualization. We propose **Gen3DGeo**, a generic conceptual model for delivering 3D city models for web visualization and navigation, based on standards. We also formalize and integrate the temporal dimension of cities with the **Gen4DCity** conceptual model. We specify this model at the logical (**Logic4DCity** model) and specification (**3DTiles_temporal** model) levels by formalizing and extending the 3D Tiles standard.

Secondly, we propose contributions for **multimedia documents and 3D city models integration** for web navigation and visualization; answering the second research question. More specifically, we propose **GenLinkable**, a generic conceptual model for features integration. We also propose the **Gen4DCity-Doc** model, which extends *Gen4DCity* with multimedia documents by using *GenLinkable*.

Thirdly, we provide **technical contributions**. An open source implementation of the contributions presented above is proposed and notes to reproduce the experiments are also provided. We propose a process for computing large-scale time-evolving 3D city models (3D city models with a temporal dimension, based on the *Gen4DCity* model) which is available in open source and reproducible. Then, we propose

a modular architecture for visualizing and navigating enhanced 3D city models on the web. We also present a methodology to achieve reuse of our software implementation and reproducibility of our experiments.

Finally, we propose a **multidisciplinary contribution** realized in collaboration with researchers of the Fab-Pat project: **DHAL** (Digital urban Heritage tools AnaLysis), a methodology designed with a multidisciplinary approach to describe, compare and analyze digital urban heritage tools.

1.4 Outline

This manuscript is structured as follows:

In chapter 2, we present a state of the art regarding three main aspects. First, we review methods and standards for 3D cities modelling and visualization on the web. Then, we describe methods for representing the temporal dimension of 3D cities. Finally, we present methods for integrating multimedia documents to 3D city models.

In chapter 3, we present the contributions related to the integration of the temporal dimension to 3D city models. We present the *Gen3DGeo*, *Gen4DCity*, *Logic4DCity* and *3DTiles_temporal* models. We also provide an open source implementation for the visualization of time-evolving 3D city models and an evaluation of the proposed models.

In chapter 4, we detail the contributions related to multimedia documents and 3D city models integration. We present the *GenLinkable* and *Gend4DGeo-Doc* models and we provide an open source implementation for navigation in documented 3D cities.

In chapter 5, we present an overview of the technical contributions realized in this thesis. We propose a process for computing time-evolving 3D city models, the software architecture of the platform designed during this thesis and we detail our methodology for interoperability, reuse and reproducibility of our research.

In chapter 6, we present and discuss the multidisciplinary collaborations that took place in this thesis. We present *DHAL* (Digital urban Heritage tools AnaLysis) and discuss how the multidisciplinary collaborations enhanced this thesis, present some limits encountered and propositions to overcome them.

Finally, chapter 7 is dedicated to conclusive elements and to the presentation of work prospects.

1.5 Reader Guidance

The models proposed in this thesis are designed with the UML¹⁵ notation. We use class diagrams for data modelling, component diagrams for software architecture and activity diagrams for processes presentation.

In the objective of providing accessible and interoperable research, we provide links to detailed procedures for reproducing the results presented in this thesis at the end of relevant sections. URLs to software resources are given using the software heritage¹⁶ archive which provides permalinks to specific versions of the code. The navigation interface of software heritage is however currently in beta version. Therefore, if you run into navigation problems, we invite you to use the Github website to access the code (the URL of original Github repository is indicated at the top of the software heritage navigation interface).

¹⁵<https://www.uml.org/>

¹⁶<https://www.softwareheritage.org/>

State of the art

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In section 2.1, we present an overview of standards and methods for modelling 3D cities. This overview is given with specific objectives stemming from chapter 1 which are to find a standard based representation of digital cities in the spatial and thematic dimensions, for interactive visualization of large-scale datasets on the web. This will serve as a basis for the two main research topic that are addressed in this thesis. This section is structured in three subsections: section 2.1.1 presents 3D city models; section 2.1.2 overview methods and formats for 3D city models visualization on the web; and section 2.1.3 sums up our findings.

In section 2.2, we present and analyze models for the temporal dimension of 3D cities. We present spatio-temporal models for geospatial information in general as well as propositions that have been integrated to 3D city models. These propositions are summed up in 2.2.1 , where we also highlight their limitations.

In section 2.3, we explore methods for integrating multimedia documents to 3D cities. This section is structured in three subsections: section 2.3.1 where we overview methods based on spatial integration and navigation; section 2.3.2 where we present methods based on thematic association; and section 2.3.3 where we summarize these propositions.

2.1 Modelling and visualizing 3D cities on the web

2.1.1 Modelling 3D cities

Many standards, methods and tools have been proposed for modelling and visualizing 3D digital cities. They stem from different fields (mainly computer graphics and geomatics) and are at different level of abstraction. Two standardization organizations are particularly active in proposing standards for geospatial information : the International Organization for Standardization¹ (with the ISO/TC 211² technical committee specialized in geographic information and geomatics) or by the Open Geospatial Consortium³ (OGC).

The ISO/TC 211 have proposed conceptual descriptions of geographic entities, for instance describing their spatial characteristics [Int19] and their temporal characteristics [Int02] that can be used for 3D cities modelling. Based on these abstract

¹<https://www.iso.org/home.html>

²<https://www.iso.org/committee/54904.html>

³<https://www.opengeospatial.org/>

propositions and on the Geographic Markup Language (GML)⁴, the OGC proposed CityGML [Kol09; Ope12], a standard format based on a structured model for urban landscapes modelling.

CityGML is composed of a thematic and of a geometric model. The thematic model is decomposed into a core module and several modules describing thematic city objects such as building, bridge, tunnel, etc. The geometric model is based on usual primitives (e.g. points, polygons, volumes). CityGML is quite flexible on data representation and allows variable degrees of structuring and coherence of the thematic and geometric models. Stadler and Kolbe [SK07] classify them in six cases, going from “Case 1: Only geometry, no semantics⁵” to “Case 6: Complex objects with structured geometry”. Figure 2.1 shows an example of a building with geometric and thematic models corresponding to cases 1 and 6. In case 1, the building is only described in the geometric dimension but with unstructured geometry (only a collection of *Polygons* grouped into a *Multi Surface*). In case 6, the thematic model and the geometric models are aligned. The building is described according to several thematic elements organized in a hierarchical structure and each element is associated with a geometric element, also organized according to the same hierarchical structure. While this freedom as to the level of structuring and coherence of CityGML data may be convenient for data producers, it makes it complex to use for researchers and software producers.

In addition, while CityGML has been widely accepted by the geospatial community and by data producers (many big cities provide their 3D city model: e.g. Lyon⁶, Berlin⁷ or New York⁸), CityGML is focused on 3D cities storing and exchange and it has not been designed for efficient visualization [Kol09].

Another important standard in the geospatial community for modelling city objects is the Industry Foundation Classes (IFC) [Int18]. However, this standard is focused on building information modelling (BIM) and on detailed geometric and thematic models of buildings and infrastructures. This format is mainly used for architecture and for the construction industry and it is not used at city scale.

⁴<http://www.ogc.org/standards/gml>

⁵Note that the semantic information is defined in the thematic model.

⁶<https://data.grandlyon.com/jeux-de-donnees/maquettes-3d-texturees-a-commune-arrondissement-2009-2012-2015-metropole-lyon/info>

⁷<https://www.businesslocationcenter.de/en/economic-atlas/download-portal/>

⁸<https://www1.nyc.gov/site/doitt/initiatives/3d-building.page>

Case 1 : Only geometry, no semantics



Case 6 : Complex objects with structured geometry

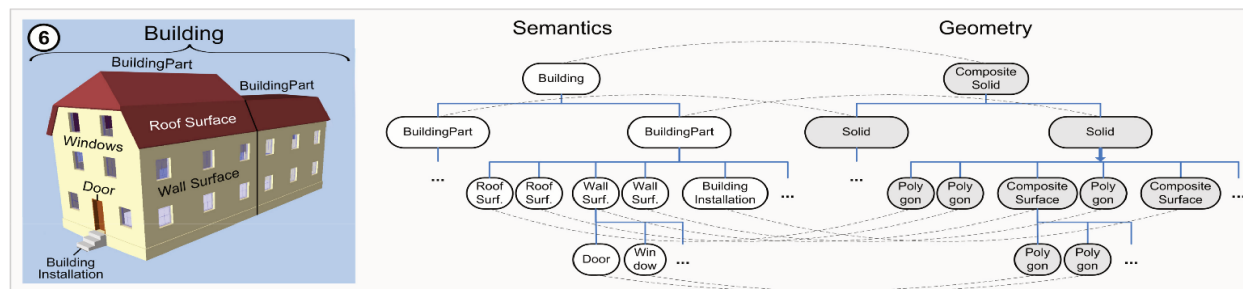


Figure 2.1.: Two cases of structuring and coherence of the thematic and geometric models of CityGML exemplified on the models of a building. Images extracted from [SK07]. Case 1 presents the model of a building with no semantics (i.e. no thematic model) and unstructured geometry. Case 6 presents structured and coherent thematic and geometric models.

2.1.2 Visualizing 3D city models on the web

Web architectures are based on clients and servers. In general, clients display information to users and servers store, compute and deliver data. Delivering content on the web for web clients requires two main elements: web services (receiving and answering queries, e.g. simple HTTP server or more evolved APIs) and data transfer formats (formats in which the response is transferred, e.g. JSON). The geospatial and the computer graphic communities proposed many web services specifications and data transfer formats over the past years, which have been used and combined to deliver 3D city models for visualization on the web.

Formats for 3D visualization on the web mainly stem from the computer graphic community. The current most efficient and most used format for 3D assets visualization on the web is glTF⁹ (GL Transmission Format). It has been proposed by the Khronos group¹⁰ which also develops OpenGL and WebGL, two APIs for rendering 2D and 3D graphics based on communication with the graphic processing unit (GPU) that have a massive impact on the computer graphic community. glTF

⁹<https://www.khronos.org/glTF/>

¹⁰<https://www.khronos.org/>

is progressively replacing Collada¹¹ and X3D¹² (in particular for applications that need good performances) which have been widely used for 3D visualization on the web these past years. In the geospatial community, the KML standard format has stand out for 3D geospatial information visualization. KML is developed by Google and it is an OGC standard since 2008. It is for instance used in the well known Google Earth. These standard formats are however focused on geometry and do not integrate thematic information (attributes and structuring) which are important aspects of 3D city models. In addition, while KML has been designed for representing geospatial data (e.g. management of coordinate reference systems (CRS)), standard formats proposed by the computer graphic community (e.g. glTF) do not have these properties.

The OGC proposed many web services for geospatial information visualization. They can be classified in two types: those delivering raster data* and those delivering vector data*. WMS¹³ (Wep Map Service) and WMTS¹⁴ (Web Map Tile Service) are the most popular for delivering raster data (they are widely used for 2D maps). The most popular web service for delivering vector data is WFS¹⁵ (Web Feature Service). Generally, the data transferred with WMS and WMTS are in well known images formats (e.g. JPEG or PNG). As for WFS, most popular data transfer formats are GeoJSON¹⁶ and JSON. GeoJSON allows to represent the geometry and thematic attributes of geographic entities. However, the geometric aspect is limited to 2D primitives, possibly with an elevation attribute allowing to represent extruded 2D objects. Finally, 3DPS (3D Portrayal Service) [Ope17a] has recently been proposed for 3D vector data (based on W3DS and WVS that are now deprecated).

Several initiatives combining these formats and web services have been proposed for delivering 3D city models for web visualization. Prieto et al. [Pri+12] visualizes 3D city models by separating the geometric and the thematic information. The geometry is managed with the X3D format and the W3DS web service, while thematic attributes are transferred in XML with the WFS web service. A screenshot of visualization of a 3D city model in their information system is presented in figure 2.2. Gaillard et al. [Gai+15] use a web service implementing 3DPS and embeds the geometry and the thematic attributes of 3D city models in JSON files (created from CityGML files). However, there is no information about the underlying conversion from CityGML to JSON nor about the data model used in the JSON

¹¹<https://www.khronos.org/collada/>

¹²<https://www.web3d.org/x3d/what-x3d/>

¹³<https://www.ogc.org/standards/wms>

¹⁴<http://www.ogc.org/standards/wmts>

¹⁵<http://www.ogc.org/standards/wfs>

¹⁶<https://geojson.org/>

files. In addition, they index the data according to a 2D regular grid index and propose a progressive loading strategy which improves visualization performances. A screenshot of visualization of a 3D city model with this proposition is presented in figure 2.3. Finally, Chaturvedi et al. [Cha+15] use the KML format along with a classic HTTP web service for the geometric information and exports the thematic information in Google Docs spreadsheets which are streamed using Google APIs. The thematic structure of 3D city models is delivered with JSON files. Similarly to [Gai+15], they index the data according to a spatial index.

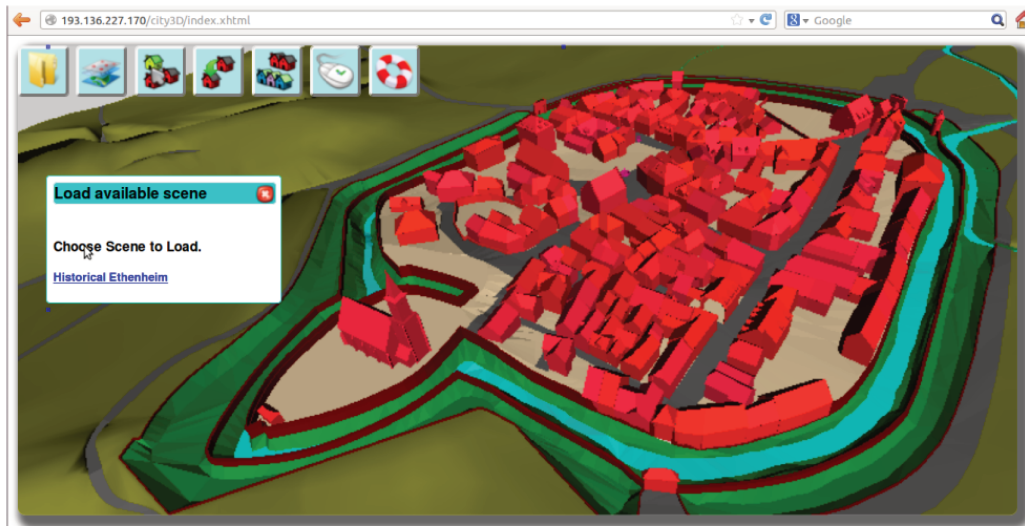


Figure 2.2.: Example fo visualization of a 3D city model with X3D and W3DS service in 2012. Image extracted from [Pri+12].

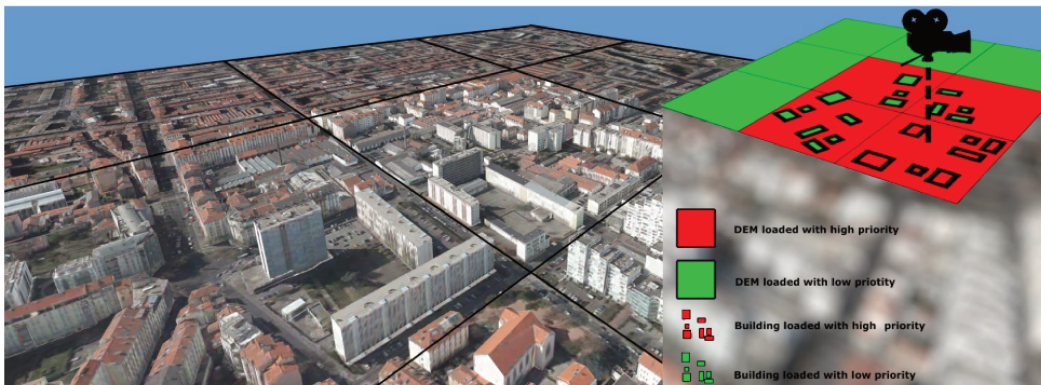


Figure 2.3.: Example of visualization of a 3D city model with JSON and 3DPS in 2015. Image extracted from [Gai+15].

Recently, two specifications have been proposed for big and heterogeneous 3D geospatial datasets visualization on the web: I3S [Ope17b] and 3D Tiles [Ope19].

They are both initiatives from companies (respectively ESRI¹⁷ and AGI¹⁸) that have been made openly available and accepted as OGC Community Standards¹⁹. These formats combined with 3DPS [Kou+18] or used with a usual HTTP server outperform the previous propositions in term of visualization performances and are being used a lot currently.

These two standards share concepts and characteristics: representation of geometric (3D polygonal models or 3D point clouds) and thematic information of geospatial data; use of spatial indexing methods to organize large datasets; and adoption of JSON and binary representations for efficient web-based operations. The main differences between these standards lie in how they represent geographic features* at the specification level: I3S has a unified way of representing geographic features, whereas 3D Tiles includes different formats: Batched 3D Model (b3dm) (for 3D polygonal models), Instanced 3D Model (i3dm) (for 3D polygonal models instanced several times, e.g. trees or street lights) and Point Cloud (pnts) for 3D point clouds. In addition, b3dm and i3dm are based on glTF for representing the 3D geometrical content.

3D Tiles and I3S are a step forward for the management of large 3D city models on the web. However, they miss one aspect of the 3D city models: the storage of their hierarchical structure. This has been made possible in 3D Tiles with the proposition or an extension of this specification (*batch table hierarchy extension*²⁰) proposed by Schilling et al. [Sch+16].

Some methods for progressive and personalized visualization of 3D city models have been proposed based on these standards [Gai+16; Gai+18], highlighting their possibilities. An example of visualization is presented in figure 2.4²¹.

2.1.3 Summary

This analysis highlights the complex background in terms of standards for 3D cities modelling and visualization on the web. Three standards currently stand out for modelling (CityGML) and web visualization (3D Tiles and I3S) of 3D city models. A summarized comparison of these standards with our needs is presented in table 2.1. ν indicates that this need is fulfilled by the standard, ν^* indicates that it is

¹⁷<https://www.esri.com/en-us/home>

¹⁸<https://www.agi.com/home>

¹⁹<https://www.ogc.org/standards/community>

²⁰<https://archive.softwareheritage.org/browse/directory/657e37e75fcc50bc0fc4e8fbb20adb6a88149a1d/?origin=https://github.com/AnalyticalGraphicsInc/3d-tiles>

²¹Note that texture is not managed on this figure but it is a feature offered by 3D Tiles and I3S.

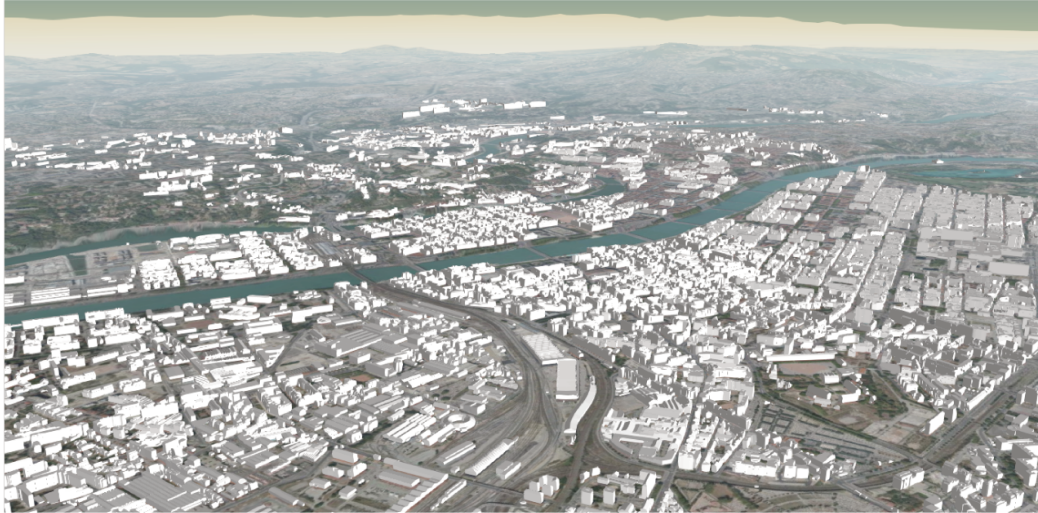


Figure 2.4.: Example of visualization of a 3D city model with 3D Tiles in 2016. Image extracted from [Gai+16].

fulfilled under certain conditions and *x* indicates that it is currently not possible or not satisfactory.

Standard	3D geometry	thematic attributes	thematic structuring	interactive web visualization of large datasets
CityGML	v	v	v	x
3D Tiles	v	v	v*	v
I3S	v	v	x	v

Table 2.1.: Comparison of the CityGML, 3D Tiles and I3S standard formats with our needs. *v* indicates that this need is fulfilled by the standard, *v** indicates that it is fulfilled under certain conditions and *x* indicates that it is currently not possible or not satisfactory.

CityGML is well established for 3D cities modelling and exchange but it is not meant for interactive visualization of large 3D city models on the web. 3D Tiles and I3S offer this possibility but I3S does not allow to represent the thematic structuring of 3D city models. It is however possible in 3D Tiles with an extension of the specification.

Despite the efforts of standardization bodies, these standards do not always move forward together and are not always harmonized. 3D Tiles and I3S for instance have been designed independently but have the same purpose. In addition, they also lack harmonization with other standards such as with ISO/TC 211 standards (e.g. with the standard terminology for geospatial information [Int08]). Furthermore,

these standards have been designed at specification level and lack conceptualization. Finally, while they have been compared and integrated in information systems [Vol18], no shared conceptual model has yet been proposed.

Based on these observations, we will propose respective and shared conceptual models for 3D Tiles and I3S, based on ISO standards and vocabulary in chapter 3. These models will serve as a basis for our two following contributions: integrating the temporal dimension and integrating multimedia documents.

In section 2.2, we review methods for modelling the temporal dimension of 3D city models, which is not yet possible with 3D Tiles and I3S.

2.2 Modelling the temporal dimension of 3D city models

The geospatial data modelling community has been particularly active on modelling the temporal dimension of geospatial information these past 30 years. First, temporal primitives and different types of time have been identified by the data modelling community [Jen+98] and have been later standardized in the geospatial community [Int02]. The two temporal primitives are *instant* and *period*. An *instant* is a “0-dimensional geometric primitive representing position in time” and a *period* is a “one-dimensional geometric primitive representing extent in time” [Int02]. A period is bounded by instants (beginning and ending points of the period). The two main types of time are: *valid time* and *transaction time*. The *valid time* is the “time when a fact is true in the abstracted reality” and the *transaction time* is the “time when a fact is current in a database and may be retrieved”. These primitives and types of time are the basis of most of temporal and spatio-temporal models for geospatial information.

Siabato et al. [Sia+18] propose a comprehensive survey of spatio-temporal models for geospatial information. They classified these models according to a typology of 18 trends in spatio-temporal modelling (see figure 2.5). These models allow to represent many types of real-world temporal events happening at various scales in space and in time, such as: buildings constructions, wilfdfires evolution, pedestrian traffic, dinners, etc. To this day, no unified model allowing to model and query all types of events and processes happening in the real world have been proposed. Most of the models have been designed or proved more efficient for specific type of changes (spatial, thematic, topological, etc.) or for different type of queries [YM02].

Modelling approach	Modelling approach	Modelling approach
Snapshot method *	Semantic-based	Moving Objects
Time-stamping *	Event-based	Graphs-based
Base state amendment vectors *	Process-based	Lifespan-based
Space-time composite model *	Ontology-based	Agents-based
Domain-based modelling *	Feature-based (Entity-based)	Kinematics
Object-Oriented	Identity-based	Ontological foundations
	Conceptual modelling extensions	

* *location-based models / changed-based approaches*

Figure 2.5.: Typology of spatio-temporal models for geospatial information proposed by [Sia+18] (image extracted from this paper).

Among the 18 trends in spatio-temporal modelling proposed by Siabato et al. [Sia+18], two in particular have been used for modelling the temporal dimension of 3D city models: *Snapshot method* and *Graphs-based*.

The snapshot model [Arm88] is an early proposition for integrating temporality in spatial databases. It consists in duplicating the tables at different time-stamps, creating several snapshots of the data. In the 3D community, several propositions are based on this model for representing the geometric evolution of spatial areas, be it a specific monument [Riz+15], a district [SD12] or a city [Nak+10]. These propositions generally focus on visual comparison of a spatial areas at different time-stamps and come along with visualization methods and tools. However, this model has several limitations. First, there is no link between spatio-temporal objects, which limits possible queries. For instance, analyzing objects life-cycle is difficult with this category of models. Secondly, these models generally do not have good performance with large datasets since objects that are in the same state at two time-stamps are duplicated.

Graph-based models for spatio-temporal geospatial information have been introduced with the *History Graph Model* [Ren96], which was further developed in [Ren00]. Renolen describes objects of the world according to three states, each of them existing during a given period: static state, changing state and dead state. The main idea is to consider change as a state i.e. being defined during a period and not as an instant event. These states and their relations have been represented by Renolen in a Statechart diagram (see figure 2.6). An object can be in a static state, it can undergo instantaneous changes and switch to a changing state. It can also die and be reincarnated.

Based on these three states, Renolen proposed the *history graph* notation (based on the Petri-nets notation [Mur89]), where static states are represented by a square rectangle, changing states are represented by boxes with circular ends and dead

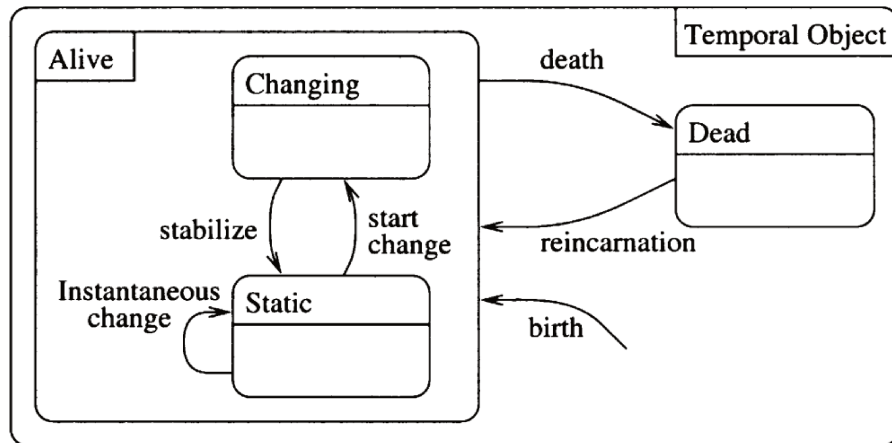


Figure 2.6.: Generic behaviour of temporal objects using the Statechart notation in the model proposed by [Ren00]. Image extracted from [Ren00].

states are represented with a rectangular box with dashed outline. Finally, Renolen proposes a typology of types of changes composed of seven types (see figure 2.7): *creation* (an object is created), *alteration* (an object is changed or modified), *destruction* (an object is destroyed or removed), *reincarnation* (an object that previously has been destroyed or removed is reintroduced, possibly with a new state and location), *merging/annexation* (two or more objects are joined together to form a new object or one or more objects are ‘swallowed’ into another object), *splitting/deduction* (an object is subdivided into two or more new objects or one or more objects is deducted from an existing object) and *reallocation* (two or more objects are merged together and two or more different objects result from the change). This typology is based on the one proposed earlier by Claramunt and Theriault [CT96].

According to [Sia+18], “While the graph-based modelling approach seems to have been put aside during the 2000s, the current decade shows an active interest in this approach”. It has for instance been used and enhanced for modelling the temporal evolution of 2D regions [Mon+10; DM+13; Dum15]. Stefani et al. [Ste+10b] propose a spatio-temporal modelling of 3D architectural sites with a focus on changes happening at the building scale and at various spatial and temporal granularity levels. Buildings of architectural sites are structured according to a spatial and thematic model designed for architectural object [DL+07]. They introduce the temporal dimension with a graph-based model, based on the proposition of Renolen [Ren00] (see figure 2.8). This proposition has been implemented in the NUBES platform, allowing visualization and navigation in spatio-temporal architectural sites as well as temporal queries on time instant (e.g. *which buildings existed at date A?*) or period (e.g. *which buildings have been constructed between dates A and B?*).

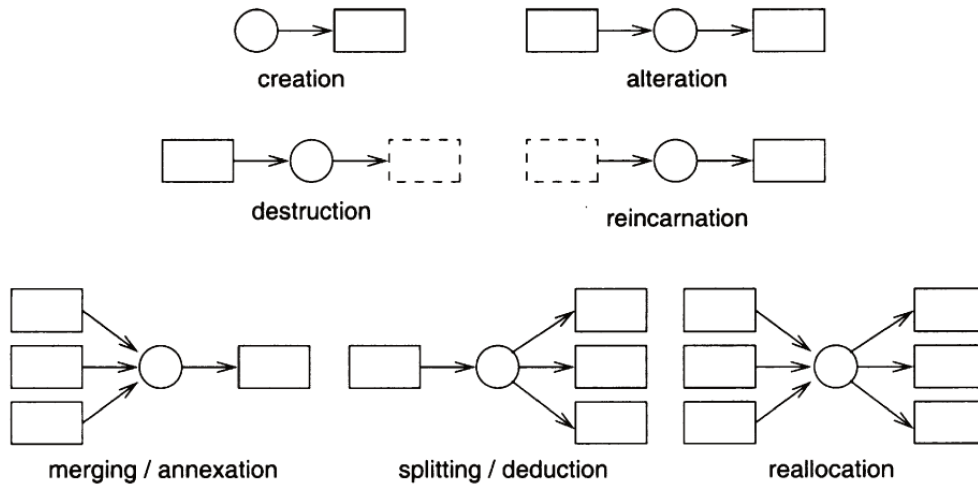


Figure 2.7.: Typology of types of changes composed of seven basic types and their representation with the notation proposed by [Ren00]. Image extracted from [Ren00].

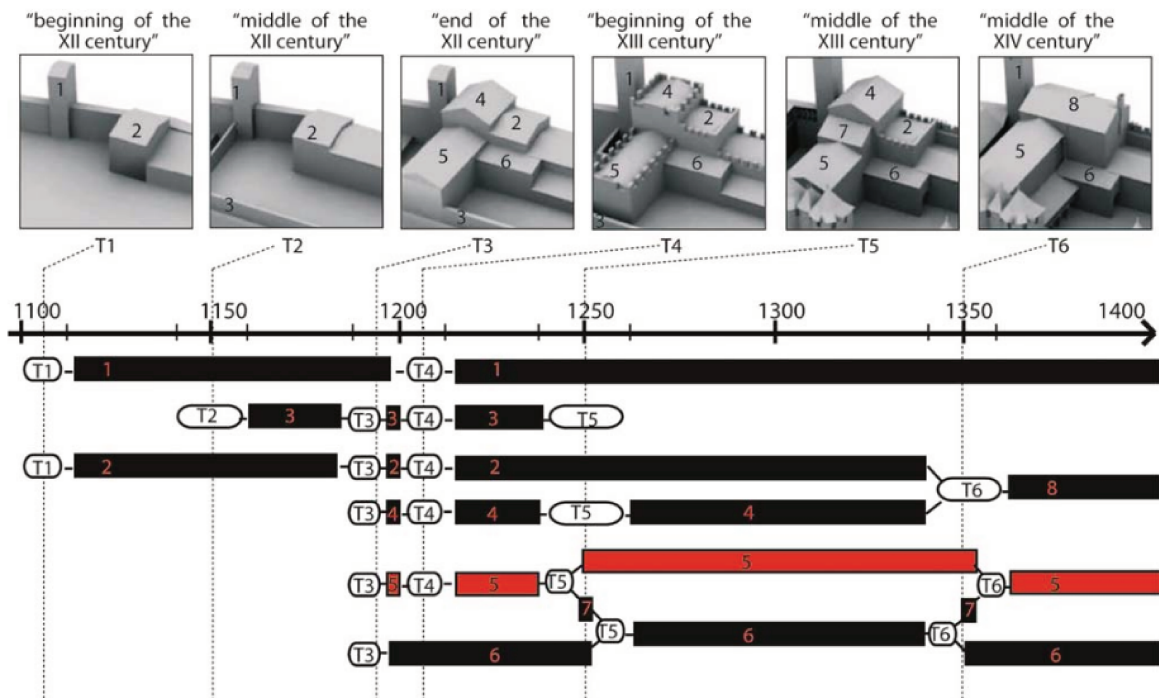


Figure 2.8.: Evolution of the Carcassonne Castle between the 12th and the 14th century according to historian Guyonnet. Image extracted from [Ste+10b].

This proposition [Ste+10b] is also described as part of other contributions with different point of views in [DL+10; Ste+10a]. In [DL+10], the authors update the typology of changes initially proposed by Renolen to: *creation*, *demolition*, *union*,

division, reconstruction and modification. These typologies plus the one proposed by Chaturvedi et al. [Cha+17] (detailed later in this section) are compared in table 2.2. Stefani [Ste10] extended this typology from an architectural and urban point of view, giving seventeen possible types of changes between two static states of a heritage building. We do not detail them here since they are specific to this application use case and are in fact combinations of the types proposed by Renolen.

Renolen [Ren00]	De Luca et al. [DL+10]	Chaturvedi et al. [Cha+17]
creation	creation	insert
alteration	modification	replace
destruction	demolition	delete
reincarnation	reconstruction	x
merging/annexation	union	x
splitting/deduction	division	x
reallocation	x	x

Table 2.2.: Comparison of typologies of temporal changes proposed in [Ren00; DL+10; Cha+17] for graph-based modelling of spatio-temporal changes. x means that this type is not defined in this typology.

Chaturvedi et al. [Cha+17] proposed an extension to CityGML for modelling the temporal dimension of 3D cities, presented as an UML model in figure 2.9. Entities in green are proposed concepts for representing the temporal dimension and the other entities are concepts from CityGML. This proposition is also based on graph modelling. First, *City Model*, *AbstractAppearance* (entity for textures representation) and *City Object* become spatio-temporal objects by inheriting *VersionableAbstractFeature*, a class defining *valid time* dans *transaction time*. *City Model*, *AbstractAppearance* and *City Object* represent objects in static states (as defined by Renolen [Ren00], see figure 2.6). Then, they introduce *Transactions* which represent changes between two *VersionableAbstractFeature* (corresponding to changing states). *Transactions* can refer to changes at various levels of spatial granularity: between city models but also between city object (e.g. building, roof, window, etc.). *Transactions* have a *type* attribute expressing the type of change that occurred. The possible values are *insert*, *delete*, *replace*. These values clearly stem from the computer science field and as we can see in table 2.2, they miss some changes types in comparison with Renolen [Ren00] and De Luca et al. [DL+10]. Chaturvedi et al. [Cha+17] also introduce the *Version* to and *VersionTransition* concepts. A *Version* is a collection of *VersionableAbstractFeature*. It represent a static state of a group of city objects for a given period. A *VersionTransition* represents a changing state between two

versions and it is composed of transactions expressing the changes that occurred between city objects of two versions. These two concepts allow to add thematic information to changes of group of city objects, adding another level of granularity in the representation of changes. They stem from the need to represent concurrent versions of evolution of the city, which may be useful for urban planning (e.g. to compare various hypothesis of evolution of a district) or for urban history evolution (e.g. to represent various hypothesis of evolution formulated by different historians). While it does not follow the notation proposed by Renolen [Ren00], figure 2.10 shows an exemple of evolution of a district and its representation with *Versions* (circles) and *VersionTransitions* (edges), allowing to grasp the idea behind these concepts. Finally, This proposition is currently being studied by the CityGML working groups for integration in the 3.0 version [Kut+20].

2.2.1 Summary

Among the great number of models that have been proposed the last 30 years, graph-based models have been the most popular way to model 3D cities evolution. According to [Sia+18], citing [Pel+04], “*the primary application of a history graph is to describe a limited extent in time and space*” and it captures “*all the knowledge we need in order to further develop a spatio-temporal system*”. Still according to [Sia+18], “*a restriction is that history graphs poorly describe the interaction between objects, e.g. split/deduction processes usually imply the creation of an additional object and the modification of another*”. In addition, they allow to keep track of the life-cycle of objects and are well suited to the main mode of navigation envisaged in our case: by switching time (i.e. instant queries), generally by switching a time slider (i.e. incrementally or decreasingly). However, their efficiency in terms of interactive visualization of large datasets remains to be assessed. In addition, typology of changes are still not well established (see table 2.2).

Chaturvedi et al. [Cha+17] proposed a graph-based model for integrating the temporal dimension to CityGML with new interesting concepts. However, as explained in section 2.1, CityGML is unfit for visualization. In addition, no implementation is proposed along with this proposition, preventing evaluation and validation with real use cases. Finally, the typology is changes is limited to three cases.

Based on these findings, we will propose contributions for integrating the temporal dimension to standards for the visualization of large 3D city models on the web in chapter 3.

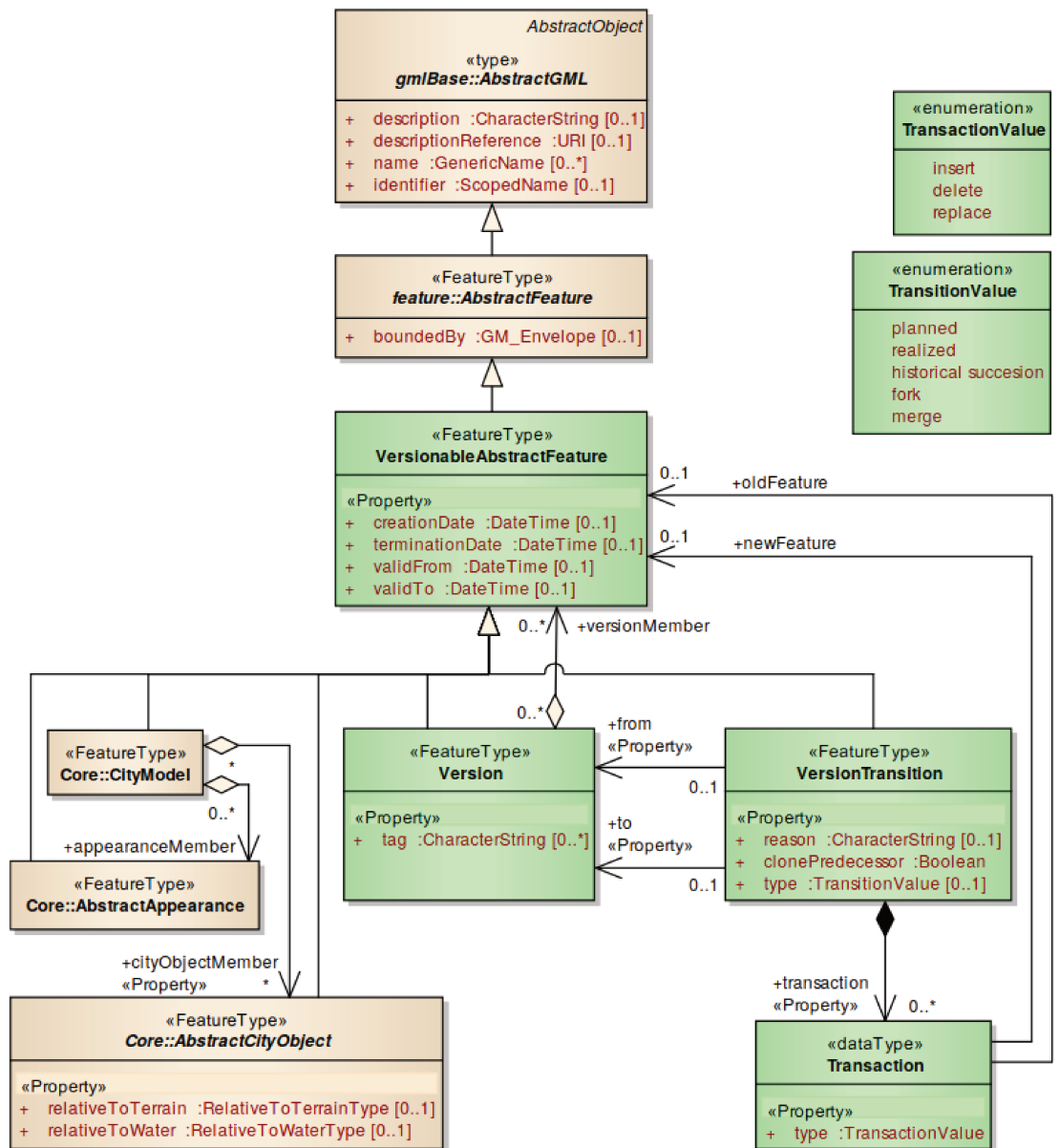


Figure 2.9.: Chaturvedi et al. [Cha+17] proposition of extension of CityGML to integrate the temporal dimension to 3D city models (image extracted from this paper).

In section 2.3, we review methods for integrating multimedia documents to 3D city models.

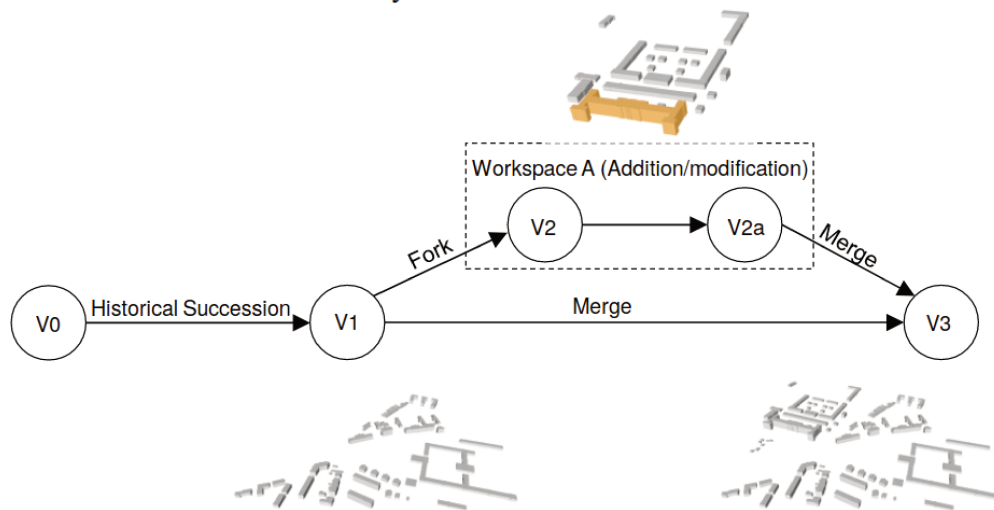


Figure 2.10.: Example of evolution of a district and its representation with *Versions* (circles) and *VersionTransitions* (edges). Image extracted from [Cha+17].

2.3 Integrating multimedia documents to 3D city models

We identified two main approaches for the integration of multimedia documents to 3D city models. The first one is based on spatial integration and navigation of graphic documents (e.g. photographs, plans, etc.) and 3D models (generally only geometric models). These propositions, generally stemming from the computer graphic community, are presented in section 2.3.1. The second category of approaches, allowing thematic association of multimedia documents and 3D city models, is presented in section 2.3.2.

2.3.1 Methods based on spatial integration and navigation

The first category of approaches consists in integrating 3D models and graphic documents in a 3D virtual environment with the documents placed in such way that there is a projective relationship between the document and the 3D model situated behind (this placement is either done manually or automatically). Then, images and 3D models can be browsed by users according to spatial and/or geometrical criteria. For instance, Snaveley et al. [Sna+06] and Brivio et al. [Bri+13] propose systems for browsing large collections of photographs placed in a 3D scene and calibrated over the 3D models they represent (see figure 2.11). Images can be browsed according to spatial criteria for answering questions such as *Which images depict a particular part of the scene ? Which images are close to a chosen one ?*



Figure 2.11.: A set of pictures calibrated over a 3D model. Image extracted from [Sna+06].

Nakaya et al. [Nak+10] propose a digital reconstruction of the city of Kyoto at different time stamps and display historical and cultural heritage multimedia contents in the 3D scene. Schindler and Dellaert [SD12] propose methods to reference images spatially and temporally and to automatically reconstruct 3D models represented by these images. Then navigation in time is possible to see the evolution of the 3D model and of the documents (see figure 2.12).

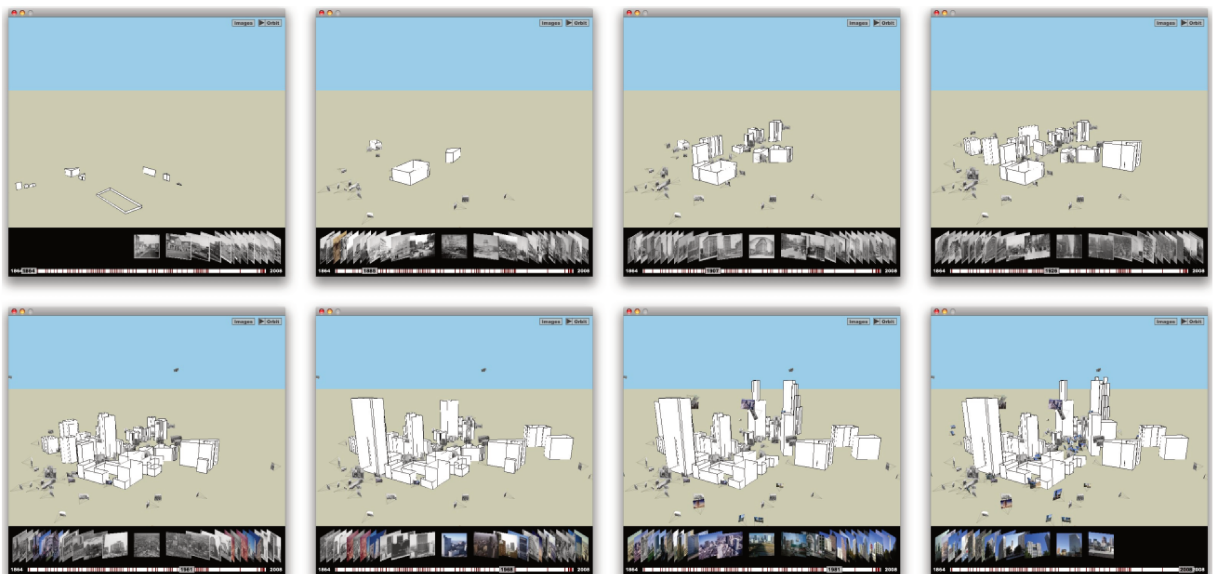


Figure 2.12.: Screenshots of the system proposed by Schindler and Dellaert to explore spatially and temporally located images and 3D models. Image extracted from [SD12].

Bruschke and Wacker [BW16] design a system for 3D reconstruction projects allowing to integrate multimedia documents sources by visualizing them inside the

3D reconstructed scene. Similarly to Schindler and Dellaert [SD12], Dewitz et al. [Dew+19] and Maiwald et al. [Mai+19] propose a method to match images and to orient them in a 4D virtual environment in order to reconstruct historical 3D models of cities and to navigate the resulting model and the multimedia documents (see figure 2.13). They also allow to display quantitative information about the multimedia documents such as the number of images in a certain area or heat maps based on images orientations.



Figure 2.13.: Screenshots of the system proposed by [Mai+19] containing spatially and temporally located images in a 3D virtual environment. Image extracted from [Mai+19].

Chagnaud et al. [Cha+16] propose different modes of visualization for multimedia documents referencing 3D city objects. Documents are geolocated and displayed as billboards in a 3D urban environment. They propose to order the documents vertically according to different layers depending on the scale of the objects they reference (e.g. documents referencing buildings are displayed in the bottom of the screen, those referencing a district are displayed above, etc.)

These methods propose new navigation possibilities in documents and 3D models with spatial (and sometimes temporal) queries through a 3D interface by moving in space (and sometimes by shifting time). However, cities are only represented by 3D geometric models and miss the thematic dimension. In addition, the temporal dimension is represented with snapshots, which we proved to be limited in section

2.2. Moreover, they do not allow to navigate from one feature to other features (e.g. from one object to a set of associated documents). Finally, they are limited to graphic documents.

In the past 20 years, De Luca participated in proposing several contributions for documenting architectural heritage with 3D models and multimedia documents and to navigate in this content. These contributions are summarized in [DL14]. First, methods for the acquisition, 3D reconstruction and structuring according to a thematic model based on morphological criteria have been proposed. Then, a method to correlate graphic multimedia documents and the 3D model to achieve a projective relation has been proposed in [Bus+10; Bus10; DL+11]. In these propositions, they also introduced the possibility to annotate images or the 3D model (e.g. by drawing regions on them). These annotations are then propagated to all the associated resources (documents or 3D models). Finally, they also propose navigation methods in this content based on three types of criteria: *spatial* (search photograph in a given viewpoint), *morphological* (query images associated to a 3D and thematic element) and *semantic* (query attributes). These propositions are integrated in the NUBES platform which also manages the temporal dimension of the architectural model and documents Stefani et al. [Ste+10b] (described in section 2.2). These propositions have been further developed and integrated into a new platform named Aioli by Manuel [Man16].

These propositions by De Luca allow to integrate images and 3D and thematic architectural elements, based on spatial criteria. They go further than the methods presented previously before that focused on images geolocation and orientation. They indeed allow more types of queries and to annotate and propagate these annotations. However, they are developed for objects at the architectural scale (i.e. a few buildings) and are not based on standards which is one of our objectives to ensure interoperability with other systems.

2.3.2 Methods based on thematic association

The need to create relations between heterogeneous elements describing cultural heritage (text, 3D model, map, photo, etc.) has been early identified by Meyer et al. [Mey+07]. They propose a model where they associate documents and archaeological objects (see figure 2.14) for designing a web based information system for the management and dissemination of cultural heritage data. In this approach, the 3D model is also considered as a document. What is also interesting is that documents can reference each other.

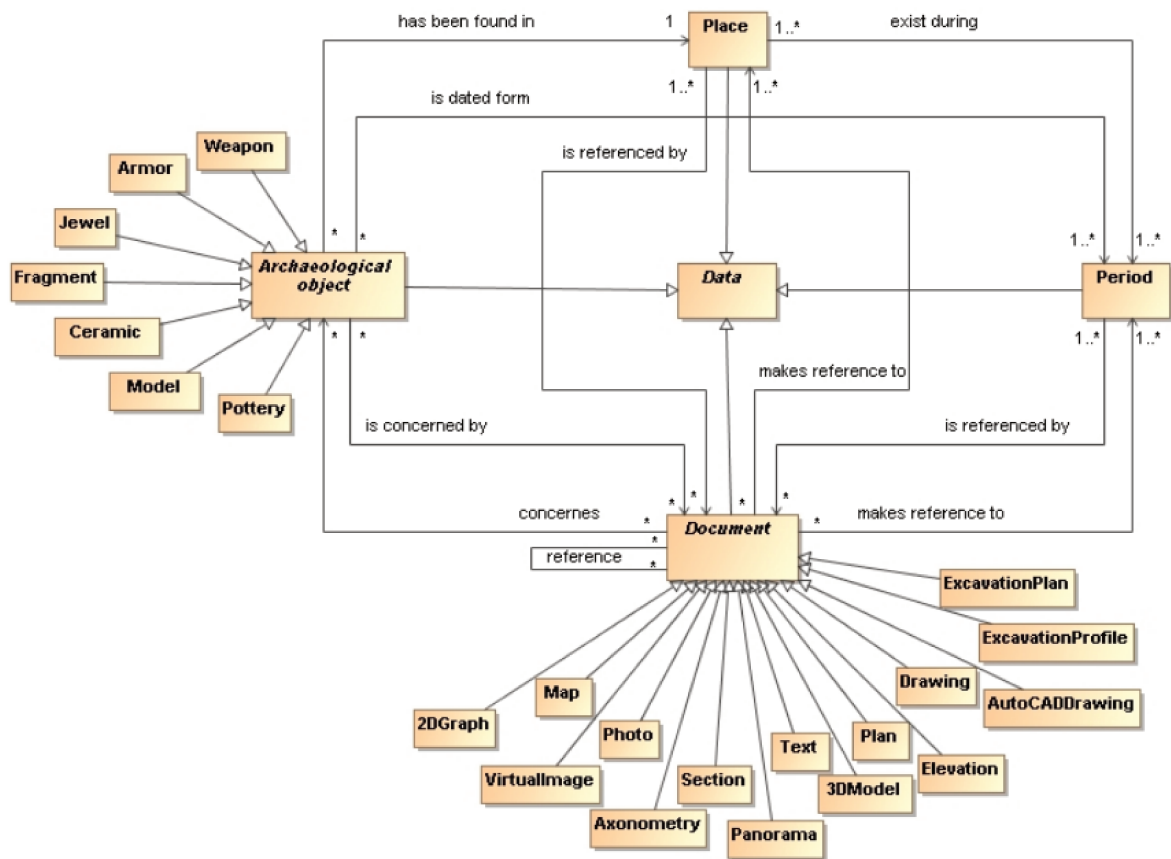


Figure 2.14.: Conceptual UML model for documenting archaeological objects. Image extracted from [Mey+07].

In a similar fashion, [Lar+15] propose a model for associating documents and 3D objects representing the harbor of Nantes in 1900. However, these two propositions [Mey+07; Lar+15] are respectively specific to archaeological objects (e.g. ceramic, weapon, etc.) and to a 3D model of the Nantes harbor in 1900, while we aim at managing large scale 3D city models (composed of geometry and structure thematic information) in general (i.e. based on standards). In addition, their management of the temporal dimension is based on adding a period of existence to the entities of their model, while we showed in section 2.2 that such models do not allow to fully grasp the evolution of city objects.

In [Her+12], they discuss the harmonization of the Nantes in 1900 project [Lar+15] with the Virtual Leodium project [Pfe+13] (which proposes a similar approach). However, this discussion is more focused on proposing a general process for the acquisition of a 3D models of historical sites and the alignment of their respective models for documents and 3D objects integration is not discussed. In addition, while [Pfe+13] propose a possible integration with the CityGML model, this proposition

has not been evaluated and has not been proposed to the CityGML community for further integration.

Samuel et al. [Sam+16] proposed an extension to CityGML for multimedia documents. The UML model they propose is presented in figure 2.15. Several aspects of this work are interesting. First, it based on standards: on CityGML for the 3D city model and on Dublin Core [Wei97; Dub12] for documents (attributes of the *DocumentObject* class). Then, the link between documents (*DocumentObject* class) and city objects (*AbstractCityObject*) is materialized with an association class (*Reference*) which contains attributes allowing to define an instant or a period of reference and to add thematic information (e.g. *purpose*). However, this proposition is specific to CityGML which is unfit for our use case. In addition, it does not allow to document the temporal evolution of the city.

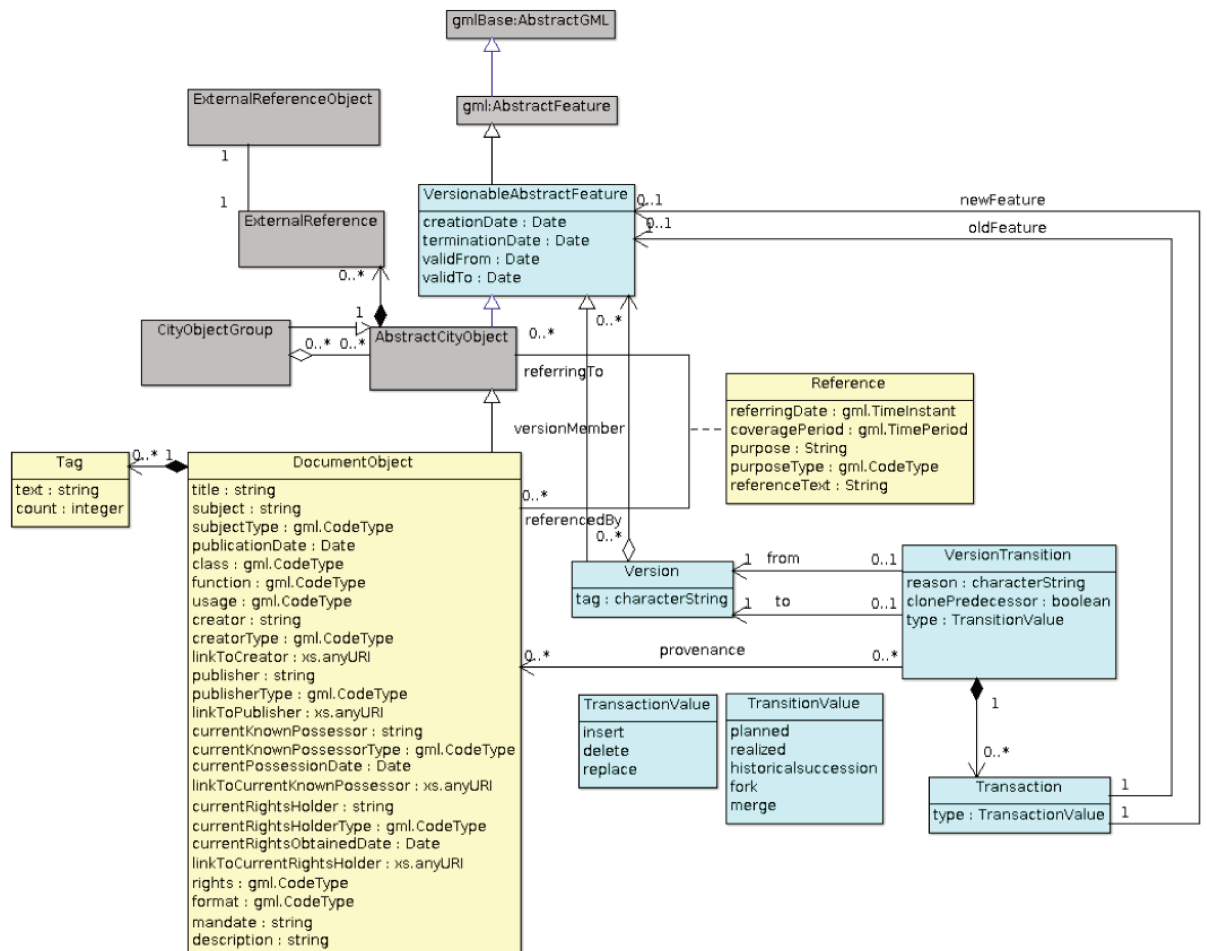


Figure 2.15.: Extension of CityGML to integrate multimedia documents. Classes in grey come from the CityGML model, those in blue are from the temporal extension proposed in [Cha+17] and those in yellow correspond to classes proposed for multimedia documents integration.

Some methods based on semantic web technologies for creating links between multimedia documents and 3D city models have also been proposed [Mé+07; Tar+12]. These contributions are based on ontologies (whether newly introduced or already existing) that describe multimedia documents and 3D city models. Then, the integration of these ontologies allow to derive semantic links between multimedia documents and 3D city models.

Finally, an interesting contribution has been made quite some years ago to design a multimedia information system for multimedia documents integration and navigation [Pap+94]. They introduce three main concepts: *Linkable Object*, *Link* and *Anchor*. Documents or composite documents can be *Linkable Objects*, enabling their linkage. A *Link* is between two *Linkable Objects* and the *Anchor* enables to specify specific parts of a document that are referred by the *Link*. Their objective and their proposition have conceptual similarities with our objective of multimedia documents and 3D city models. However, their proposition is limited to multimedia documents.

2.3.3 Summary

Among the propositions for multimedia documents and 3D objects integration, none fulfills all our objectives at the same time. They indeed either focus on:

- Specific use cases and hence the proposed models depend on this use case (e.g. architectural heritage);
- Specific dimensions of city objects (e.g. only spatial and documenting the temporal evolution of objects is rarely possible).
- Specific types of navigation (spatial or thematic)

While, spatial integration and navigation has been explored a lot, propositions for thematic and temporal integration and navigation of multimedia documents and 3D city models are still not fully satisfactory. However, the propositions of [Sam+16] (because it allow thematic integration of multimedia documents and 3D city models) and of [Pap+94] (because of the conceptual similarities and propositions) are the closest to meeting our needs. We will base our contributions to integrate multimedia documents to 3D city models on these methods in chapter 4.

Delivering time-evolving 3D city models for web visualization

Contents

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The work presented in this chapter has been accepted for publication in the *International Journal of Geographical Information Science* [Jai+20a].

In this chapter, we present our contributions for the visualization of time-evolving 3D city models on the web. We name time-evolving 3D city models, 3D city models with their temporal dimension. We focus on enhancing standard formats with a formalization of this temporal dimension. In this objective, we propose the following contributions and outline:

- **Developing a generic conceptual model** (*Gen3DGeo*) for delivering 3D geographic features for web visualization based on standard formats (3D Tiles and I3S) (section 3.1.1)
- **Formalizing and integrating the temporal dimension** of cities in this model (*Gen4DCity* model) (section 3.1.2)
- **Specifying** this model at **logical** (*Logic4DCity* model) and **technical** (*3DTiles_temporal* model) **levels** by formalizing and extending the 3D Tiles standard (section 3.2)
- **Implementing** the proposed approach in **open-source** web software, **evaluating** software performance and **documenting** the procedures to ensure **reproducibility** (section 3.3)

We finish this chapter with a discussion on the contributions and on potential future leads (section 3.4).

3.1 Generic conceptual models

3.1.1 Conceptual model of 3D geospatial web standard formats

Figure 3.1 presents **Gen3DGeo**: a generic conceptual model for delivering 3D geographic features for web visualization based on standard formats (3D Tiles and I3S). This model is an abstraction of the 3D Tiles and I3S standards. The names of the entities are independent from 3D Tiles and I3S and are based on [Int08] in the objective of alignment with existing standards. As a prior step to this model, we also designed conceptual models of 3D Tiles and of I3S (see Appendix A).

Geographic Features (e.g. building, roof, bridge, etc.) can have a *Geometry* (e.g. point cloud, polygonal model, etc.), and *Thematic Attributes* (e.g. owner). These

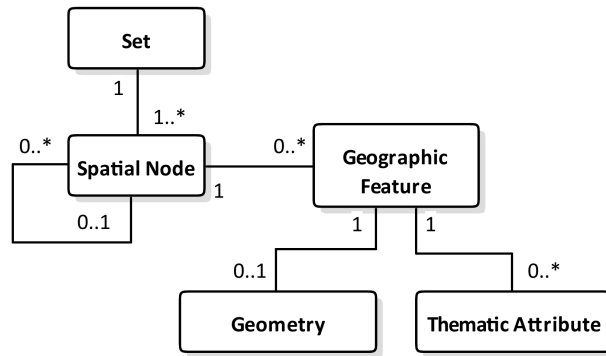


Figure 3.1.: **Gen3DGeo:** Generic conceptual model for delivering 3D geographic features for web visualization based on standard formats (3D Tiles and I3S)

Geographic Features are organized according to a spatial indexing method (e.g. quadtree, octree, etc.). The resulting index is represented by a set of related *Spatial Nodes* (that is to say nodes computed according to spatial criteria), most frequently representing a tree. 3D Tiles and I3S both offer the possibility of having multiple indexes, aggregated in a root object. This root object is represented by *Set* in our model. In the case of 3D Tiles, a *Spatial Node* can either directly reference a set of *Geographic Features* or another new index (i.e. another *Spatial Node* hierarchy). In the case of I3S, indexes are grouped into layers (representing a layer of data, e.g. a building layer), which are grouped together in the scene. Finally, 3D Tiles and I3S make it possible to represent geographic features at various levels of detail. This is represented through the *Spatial Nodes* hierarchy: a child *Spatial Node* can be a refinement of its parent.

This synthetic representation expresses the shared concepts of 3D Tiles and I3S. It allows to work on these standards at the conceptual level (e.g. to extend them) without being tied to one or the other. It also makes it possible to abstract the implementation choices, facilitating the learning of underlying concepts. In section 3.1.2, we formalize the temporal dimension of cities and integrate it to this model.

3.1.2 Formalization and integration of the temporal dimension

Figure 3.2 presents **Gen4DCity**: a generic conceptual model for delivering *time-evolving* 3D city models on the web. This model extends *Gen3DGeo* (in white) with our proposed formalization of the temporal dimension (in gray). Additional information about data types and enumerations used in this model and in the following models of this chapter are presented in figure 3.3. While *Gen3DGeo* is generic to geographic features, the formalization of the temporal dimension we

propose has been designed and tested for cities and not for all type of geographic features. Therefore, the following model is named *Gen4DCity* and not *Gen4DGeo*.

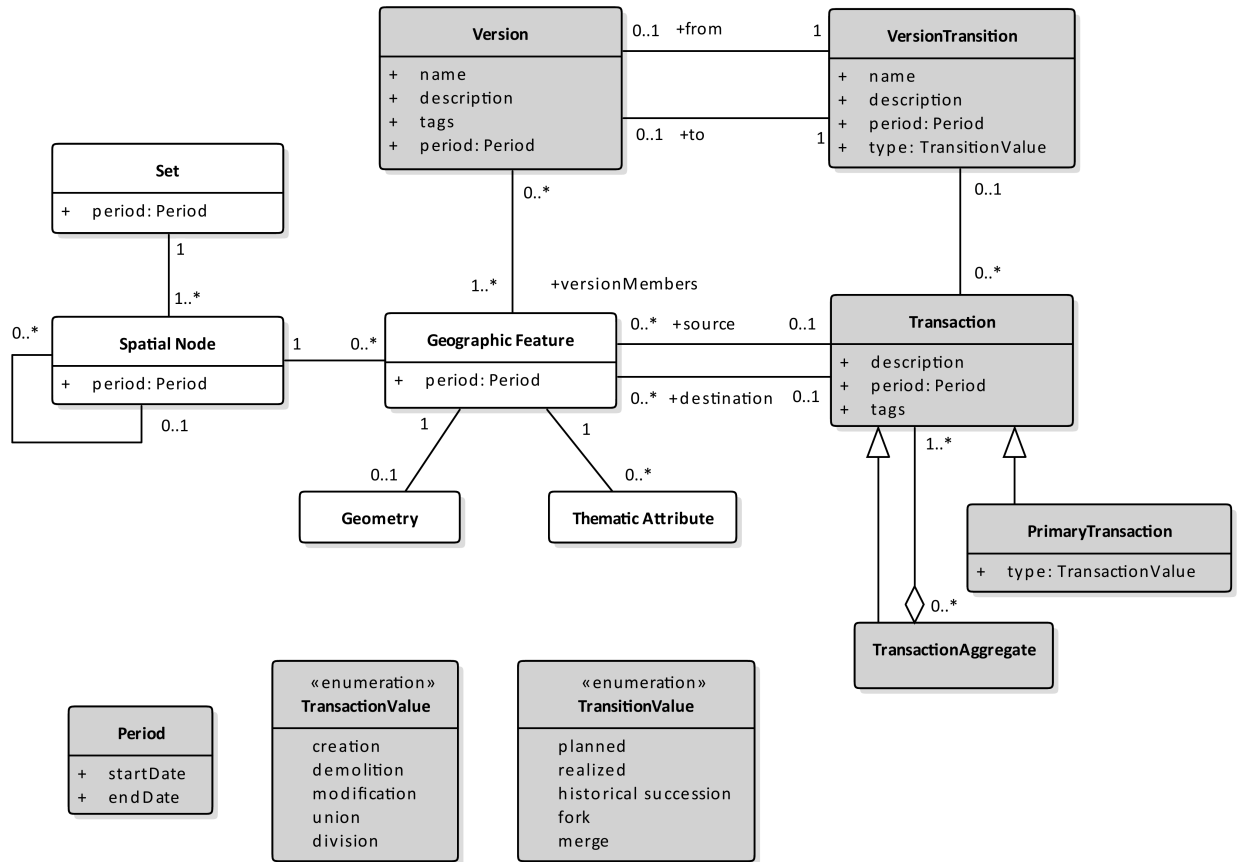


Figure 3.2.: *Gen4DCity*: Generic conceptual model for delivering time-evolving 3D city models on the web based on standard formats. The entities of *Gen3DGeo* (from figure 3.1) are depicted in white. The proposed formalization of the temporal dimension is depicted in gray.

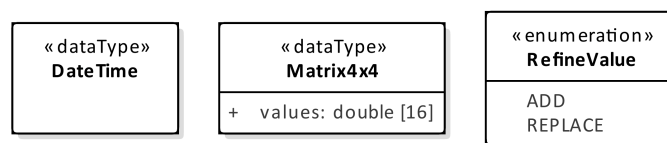


Figure 3.3.: Data types and enumeration used in figures 3.2, 3.5 and 3.6.

First, we introduce the *Period* entity (lower-left corner of figure 3.2) which represents an interval of time (based on [Int02]). A *Geographic Feature* can now have a *Period*, making it possible to represent its valid time in the real world (e.g. a building built in 1975 and destroyed in 2012). *Spatial Nodes* can also be associated with a *Period*, introducing the possibility to use spatio-temporal indexing methods [The+98; Had+02; Mok+03] or temporal indexing methods [Ber+97]. These indexing

methods are more suited (while generally harder to implement) than spatial indexing methods. Since the choice of the indexing method is highly dependent on the data and application use case, we give the possibility to choose the most suited method to users of our model. A *Set* can also be associated with a *Period*, making it possible to store its total time of existence for instance.

Next, we introduce the *Transaction* entity to represent the changes between geographic features. This concept is inspired from [Cha+17] and represents a changing state as defined in [Ren00]. However, it has been adapted in the following way. A *Transaction* is composed of a *description* and *tags*. Two specifications of *Transaction* are introduced: *PrimaryTransactions* and *TransactionAggregates*. The idea behind this proposition is to allow to combine primary transactions to compose more complex transactions. *PrimaryTransactions* have a *type* attribute which can have one of the following five values: *creation*, *demolition*, *modification*, *union* or *division*. These types are defined in the *TransactionValue* enumeration and are inspired from [Ren00; Ste+10a; Cha+17]. We argue that these five primary types allow to form the other types of transactions encountered in the literature. For instance, Renolen [Ren00] proposes six types of transaction between geographic features (figure 2.7), five of which correspond to the primary types we propose. However, the sixth one (*reincarnation*) can be modeled using a *TransactionAggregate* composed of two *PrimaryTransactions* of the types *demolition* and *creation* (this example is illustrated in figure 3.4). This model for transactions has two main advantages. First, it is more generic than the current solutions because it does not restrict transactions types to a limited set of predefined types that are highly dependent on the data and application use case. For instance, some types may be needed for cultural heritage studies while others may be needed for architectural studies. The second main advantage is the possibility to represent the *Transactions* at different levels of detail. Take for instance, the *reincarnation* type proposed by Renolen [Ren00]. It can be seen at a macro level of detail (*TransactionAggregate*) or at a finer grain, with both *PrimaryTransactions* of the types *demolition* and *creation* (figure 3.4).

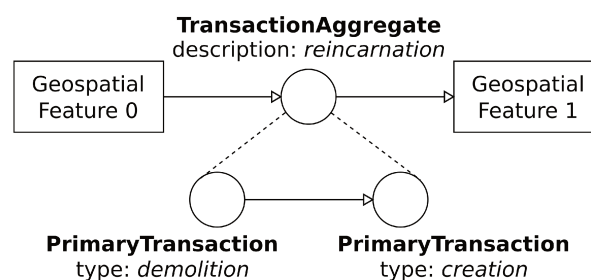


Figure 3.4.: Aggregated transaction example.

Then, we introduce the *Version* and *VersionTransition* entities (inspired from [Cha+17]). *Versions* allow to group spatio-temporal geographic features for two main use cases. First, it allows to group geographic features having hierarchical relations (e.g. a building, its roof and walls) to form different versions of these groups. The second purpose is to express concurrent versions of evolution of a group of geographic features. For instance, in the case of the renovation of a district, several projects may be proposed. A version may be created to represent each one of these projects. *VersionTransitions* can be used to express transitions between *Versions*. *VersionTransitions* can be composed of *Transactions* and have a type defined in the *TransitionValue* enumeration.

This formalization of the temporal dimension has two main advantages compared to existing solutions. First, it makes it possible to represent the evolution of the city over time on different spatial and thematic scales (city level, geographic features level) and covers many types of *Transactions* between *Geographic Features*. The second main advantage is its flexibility; we can represent the evolution of the city at various degrees of precision depending on its data and needs. The first possibility is to only use the *Period* entity. This allows us to represent different states of *Geographic Features* and of the *Set*, and to use a spatio-temporal or temporal indexing method to organize the data. The second possibility is to also use the *Transaction* entity. This way, it is possible to represent the transactions between *Geographic Features*. The third possibility is to use all the entities formalizing the temporal dimension in this model. This provides the additional opportunity of grouping *Geographic Features* together in *Versions* and representing the transitions between these *Versions* with *VersionTransitions*.

In section 3.2, we specify *Gen4DCity* at the logical and specification levels in the 3D Tiles standard format.

3.2 Specification into 3D Tiles

3.2.1 3D Tiles logical model and temporal extension

Figure 3.5 presents both **Logic3DGeo** and **Logic4DCity**. *Logic3DGeo* (in white) is a proposition of logical model of the 3D Tiles standard. It depicts the current state of 3D Tiles (version 1.0) [Ope19] and covers all the data modelling part of the specification. *Logic3DGeo* is a specification of *Gen3DGeo*. *Logic4DCity* is a logical model for delivering *time-evolving* 3D city models on the web. It integrates the

formalization of the temporal dimension to *Logic3DGeo*. *Logic4DCity* is a specification of *Gen4DCity*. The recursive composition association of *Geographic Feature* (thick line) is a proposition of conceptual representation of hierarchical relationships between geographic features of 3D city models (i.e. a conceptual representation of the batch table hierarchy extension of 3D Tiles¹).

3D Tiles is composed of a *Tileset* (corresponding to *Set* of *Gen3DGeo*). *Asset*'s attributes *version* (version of 3D Tiles) and *tilesetVersion* (identifier for tracking updates of a *Tileset*) are not related to representing the evolution of the city over time. A *Tileset* is composed of a set of *Tiles* (corresponding to *Spatial Nodes* of *Gen3DGeo*). Each *Tile* has up to two *BoundingVolumes*: *boundingVolume* and *viewerRequestVolume*. The *viewerRequestVolume* makes it possible to specify a volume where the tile must be displayed (i.e. the content of the tile is displayed only if the camera is inside this volume). Each *Tile* has a *TileContent* that can also have a *BoundingVolume*, which must closely fit the geographic features of the tile. The *TileContent* references either a *Tileset* or a *FeatureSet*, which is a collection of *Geographic Features* plus some *FeatureSetProperty* (e.g. number of points, offset, scale, etc.). The *FeatureSet* entity depicts a generalization of the formats proposed by the 3D Tiles community to represent geographic features: Batched 3D Model (b3dm), Instanced 3D Model (i3dm), Point Cloud (pnts) and Composite (cmpt). A *Geographic Feature* (corresponding to *Geographic Feature* of *Gen3DGeo*) can have a *Geometry* (*Geometry* of *Gen3DGeo*). It can also have *FeatureProperties* (*Thematic Attribute* of *Gen3DGeo*) such as application-specific attributes (e.g. the owner of a building) or appearance information (e.g. color or texture coordinates). A *Geometry* can belong to several *Geographic Features*, so it is possible to have a 3D model instanced several times (e.g. with different positions or different scales such as in the i3dm format). At the technical specification level, a *Thematic Attribute* is stored in a batch table or in a feature table depending on the property and on the format (b3dm, i3dm, etc.).

We integrate the formalization of the temporal dimension proposed in *Gen4DCity* with the entities in gray. Most of the concepts have been integrated by direct mapping from *Gen4DCity* thanks to the abstract modelling work done in section 3.1 and to the mapping of *Gen3DGeo* to *Logic3DGeo* described above. *VersionTransition*, *Version* and *Transaction* are aggregated in the *Tileset* since they are associated with *Geographic Features* across the *Tileset* (i.e. that can be in different *Tiles*). The *Spatial Node's Period* (from *Gen4DCity*) is aggregated in the *Bounding Volume* and not in the *Tile* (which could have been done by direct mapping since *Spatial Node* is mapped to *Tile*). This way, not only can the *Tile's boundingVolume* attribute have a

¹<https://archive.softwareheritage.org/browse/directory/657e37e75fcc50bc0fc4e8fbb20adb6a88149a1d/?origin=https://github.com/AnalyticalGraphicsInc/3d-tiles>

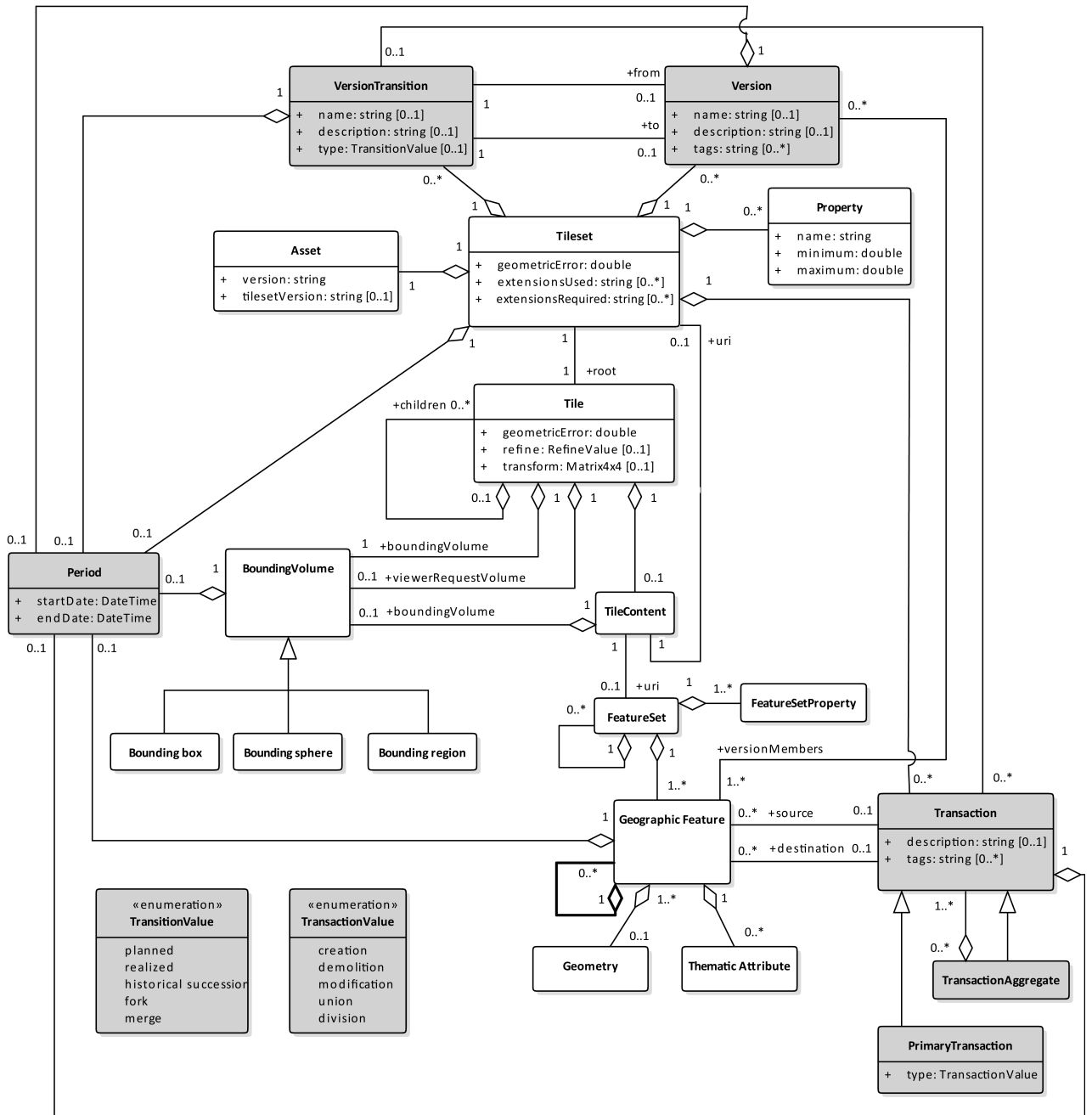


Figure 3.5.: Logic4DCity: logical model for delivering time-evolving 3D city models on the web based on extending 3D Tiles. A logical model of 3D Tiles, **Logic3DGeo**, is proposed in white and the temporal extension is represented in gray. The recursive composition association of *Geographic Feature* (thick line) is a conceptual representation of the *batch_table_hierarchy* extension of 3D Tiles.

Period, but also its *viewerRequestVolume* and the *TileContent*'s *boundingVolume*. The *boundingVolumes* make it possible to index *Geographic Features* using spatio-temporal

indexing methods. The *viewerRequestVolume* makes it possible to show the content of a *Tile* only when the display date (date at which the data is displayed to the user) is inside its *Period*.

In section 3.2.2, we propose the technical specification of the temporal formalization. This technical specification is an extension of 3D tiles. We name it **3DTiles_temporal** (following the naming convention of 3D Tiles extensions).

3.2.2 Technical specification of the temporal extension

3D Tiles contains concepts named *extension* and *extra* that allow to extend the core specification. Figure 3.6 is a proposition of description of these concepts. *Extension* makes it possible to extend 3D Tiles entities. It has a *name* and it is composed of an application-specific *Object*. An *Object* can be composed of other *Objects* and/or *Attributes*. *Extensions* can be aggregated in an *ExtensionSet*. An *ExtraSet* is a collection of *Extras*. An *Extra* is an application-specific *Attribute*, making it possible to add specific metadata to 3D Tiles entities. All the entities of the 3D Tiles specification can have an *ExtensionSet* and an *ExtraSet*. In other words, all the implemented classes of *Logic3DGeo* (i.e. of the 3D Tiles specification) can have an *ExtensionSet* and an *ExtraSet*.

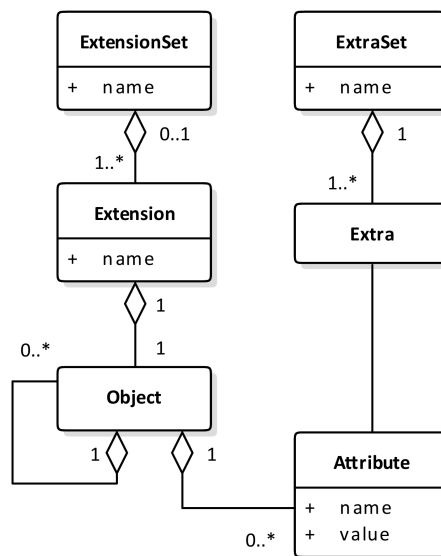


Figure 3.6.: Description of the concepts for extending 3D Tiles.

The *3DTiles_temporal* extension specification is described with JSON schemas, which we make available online². It uses the *Extension* concept. This way, the core of the standard is not modified, but there is still an impact on users of 3D Tiles.

The specification is composed of three *Extension* objects respectively aggregated in *Tileset*, *BoundingVolume* and *BatchTable*. The extension of the *Tileset* has a *startDate* and an *endDate* and stores *versions*, *versionTransitions* and *transactions*. The extension of the *BoundingVolume* also has a *startDate* and an *endDate* to allow the representation of 4D bounding volumes and hence the use of spatio-temporal indexing. The *BatchTable* is where the thematic attributes of features are stored. We extend it with two arrays representing the time of existence of each *Feature*, namely *startDates* and *endDates*. The extension of the *BatchTable* also holds an array of identifiers of *Features*, enabling their referencing in *transactions* and *versions*. This specification results from models previously presented and in particular from *Logic4DCity*.

The models proposed in this section allow to model the temporal dimension of 3D city models by extending the 3D Tiles standard format. In particular, they allow to keep track of the evolution of 3D city models' features at various granularity levels and to add thematic information to these, which was some of the challenges stated in the introduction of this chapter. In the next section, we propose an implementation of these propositions, demonstrating that they allow to achieve *interactive* spatio-temporal visualization of *large-scale* time-evolving 3D city datasets on the web.

3.3 Implementation and evaluation

In this section we present an implementation allowing to deliver and visualize time-evolving 3D city models on the web with the *3DTiles_temporal extension* proposed in this chapter. We start with a presentation of the software architecture (section 3.3.1). We continue with an evaluation of our propositions in comparison with existing standards (section 3.3.2). We finish with the proposition of visualization rules for urban evolution visualization and apply them for the visualization of a time-evolving 3D city model (section 3.3.3).

²<https://doi.org/10.5281/zenodo.3596881>

3.3.1 Software architecture

We propose an open-source web prototype allowing to create, deliver and visualize time-evolving 3D city models, implementing the *3DTiles_temporal* extension. The software architecture of this prototype is represented in figure 3.7. In this section, we only give an overview of this architecture to facilitate understanding of the evaluation of our contributions. A more detailed view of the software architecture and implementations are presented in chapter 5.

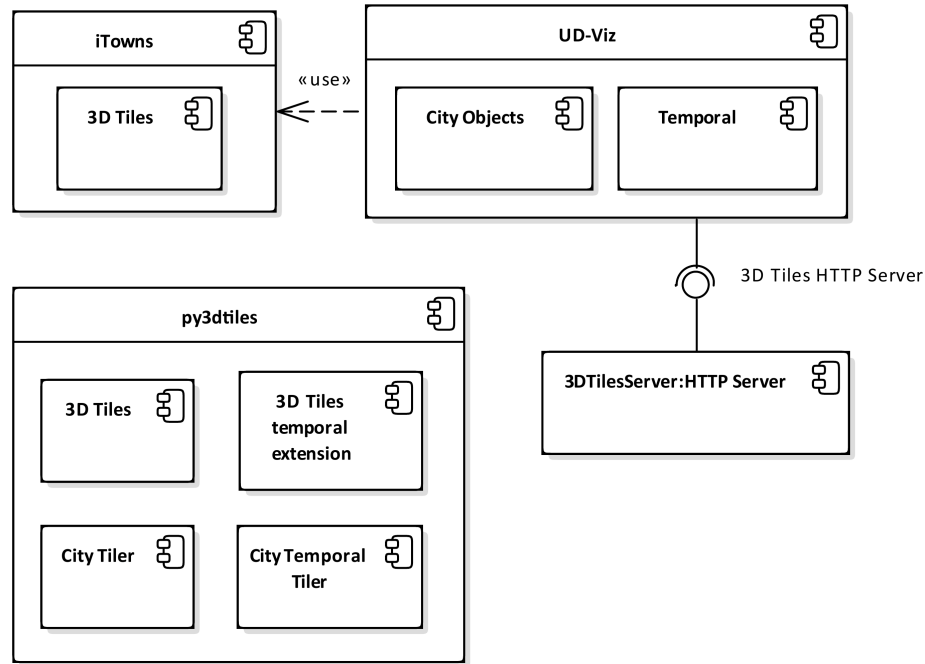


Figure 3.7.: Software architecture for creating, delivering and visualizing time-evolving 3D city models, implementing the *3DTiles_temporal* extension.

*py3dtiles*³ allows to create 3D Tiles datasets from various sources (e.g. 3DCityDB [Yao+18], LAS files [PRS11], etc.). We contributed to the implementation of the 3D Tiles specification in *py3dtiles*. In addition, we implemented the *batch_table_hierarchy* extension of 3D Tiles (allowing to represent hierarchical relations between objects) and the *3DTiles_temporal* extension. We also implemented two processes respectively allowing to create 3D city models in 3D Tiles (*City Tiler*⁴) and time-evolving 3D city models in 3D Tiles extended with *3DTiles_temporal* (*City*

³<https://archive.softwareheritage.org/swh:1:rev:27c1ec918630215002da5e2115fa5d3775ed5210;origin=https://github.com/Oslandia/py3dtiles/>

⁴<https://archive.softwareheritage.org/swh:1:cnt:3fe3b38bf74758e1ac649e16d05c3c11f09076d4;origin=https://github.com/VCityTeam/py3dtiles/>

*Temporal Tiler*⁵). The *City Tiler* process allows to go from a 3DCityDB database containing 3D city objects to 3D city models in 3D Tiles with tiles represented in the b3dm format. The *City Temporal Tiler* takes two inputs: 3DCityDB databases containing time-stamped city models of the same spatial area and a graph containing the transactions between the features of these city models. From these inputs, it computes a time-evolving 3D city model in 3D Tiles extended with *3DTiles_temporal*, with tiles represented in the b3dm format. This process, as well as the pre-processing steps allowing to compute the graph of transactions are fully detailed in section 5.1. This implementation is currently available on a specific version of *py3dtiles*⁶. They are planned to be integrated to the main version of *py3dtiles* after a few steps of cleaning and refactoring.

The produced time-evolving 3D city dataset can be exposed through any *HTTP server* (*Apache* in our case) and can be visualized in the *UD-Viz*⁷ web client. *UD-Viz* allows to visualize, analyze and interact with geographic data (3D city models, vectorial resources, maps, etc.). It is based on *iTowns*⁸, a framework for visualizing 3D geographic data. We contributed to the implementation of 3D Tiles in *iTowns* to make it more compliant with the specification and more flexible. In particular, it is now possible to declare 3D Tiles extensions and associated applicative code in a web client using *iTowns* and to plug them to *iTowns* from this web client. The *3DTiles_temporal* is implemented this way in the *Temporal* module of *UD-Viz*. This *Temporal* module is also in charge of the interfaces related to the temporal aspect (see section 3.3.3 for screenshots and for an example use case). The *City Object* module of *UD-Viz* allows to interact with city objects in the 3D scene (e.g. to display thematic information of a building selected from the 3D scene). These implementations are currently available on specific versions of *UD-Viz*⁹ and of *iTowns*¹⁰. They are planned to be integrated to the main versions of *iTowns* and *UD-Viz* after a few steps of cleaning and refactoring.

⁵<https://archive.softwareheritage.org/swh:1:cnt:e9fca4145806c85d1ab4eec05cba628311fd3370;origin=https://github.com/VCityTeam/py3dtiles/>

⁶<https://archive.softwareheritage.org/swh:1:rev:39b23180b47ed3b995aeb5b8fa45aff56b88d353;origin=https://github.com/VCityTeam/py3dtiles/>

⁷<https://archive.softwareheritage.org/swh:1:rev:b5a523825862a3f2dd440c2922485cdd30009834;origin=https://github.com/VCityTeam/UD-Viz/>

⁸<https://archive.softwareheritage.org/swh:1:rev:e996369f1da742b8ca923f4c64d656f8d1a537db;origin=https://github.com/iTowns/itowns>

⁹<https://archive.softwareheritage.org/swh:1:rev:e915ff94f9902fa0def310e159beb3caf461ab59;origin=https://github.com/jailln/UDV/>

¹⁰<https://archive.softwareheritage.org/swh:1:snp:1f61a61af2dc46834e108c586373f043defcd687;origin=https://github.com/jailln/itowns/>

Since the formalization of the temporal dimension has been integrated to 3D Tiles as an extension (following the recommendations of the standard), it could be implemented into other software components supporting 3D Tiles (e.g. Cesium¹¹).

3.3.2 Experiments and evaluation

The objectives of this section are to evaluate the scalability and the interactivity of the *3DTiles_temporal* extension. In particular, we show that it allows to visualize *large-scale* time-evolving 3D city models while allowing *interactive* spatio-temporal navigation. First, we present the dataset and the different standard representations chosen for this evaluation (section 3.3.2). Secondly, we evaluate the interactivity of the spatio-temporal navigation (section 3.3.2).

Datasets comparison

In order to evaluate the *3DTiles_temporal extension*, we use a dataset representing the buildings of the city of Lyon, France (48 km²) between 2009 and 2015. We stored this dataset in three different ways: in CityGML, in 3D Tiles and in 3D Tiles extended with *3DTiles_temporal*. We name these representations **DS-CityGML**, **DS-3DTiles** and **DS-3DTiles-Tmp** respectively.

DS-CityGML is composed of three independent snapshots of the city of Lyon (2009, 2012 and 2015). The original data has been downloaded from the *Grand Lyon open data website*¹². However, it has some quality issues. In particular, it has syntax errors, the data structure and the version of CityGML are not the same between vintages (2009, 2012, 2015). A pre-processing step allowed to correct these issues. In addition, *DS-CityGML* has been simplified by removing textures coordinates and generic thematic attributes that are not included in *DS-3DTiles* and *DS-3DTiles-Tmp*. These quality issues are investigated in more depth in section 5.1. The pre-processing steps involved for creating *DS-CityGML* are presented in more details in section 5.1.

DS-3DTiles is composed of the same three independent snapshots (2009, 2012 and 2015) of the buildings of the city of Lyon than *DS-CityGML*. It has been created by converting each snapshot of *DS-CityGML* into the 3D Tiles format with the *City Tiler* of *py3DTiles* presented in section 3.3.1.

¹¹<https://cesiumjs.org/>

¹²<https://data.grandlyon.com/>

DS-3DTiles-Tmp represents the buildings of Lyon between 2009 and 2015 but stored as a time-evolving 3D city model in 3D Tiles extended with *3DTiles_temporal*. It contains states of buildings along with periods and transactions between these states. It has been computed with the *City Temporal Tiler* of *py3DTiles* presented in section 3.3.1. The input data are *DS-CityGML* and a list of changes between the vintages. This list of changes has been computed with a geometric comparison between the vintages, implementing the method described in [P  +15]. The process for creating this dataset is presented in more details in section 5.1.

Table 3.1 compares the size in Megabytes of *DS-CityGML*, *DS-3DTiles* and *DS-3DTiles-Tmp*, as well as the number of buildings they store.

Dataset		Size (MB)	Number of buildings
DS-CityGML	2009	1100	14827
	2012	1110	14835
	2015	976	24289
	Total	3176	53951
DS-3DTiles	2009	182	14827
	2012	183	14835
	2015	261	24289
	Total	626	53951
DS-3DTiles-Tmp		435	36975

Table 3.1.: Comparison of a dataset representing the buildings of the city of Lyon, France (48 km²) between 2009 and 2015, stored in three different ways: in CityGML (*DS-CityGML*), in 3D Tiles (*DS-3DTiles*) and in 3D Tiles extended with *3DTiles_temporal* (*DS-3DTiles-Tmp*).

Table 3.1 shows that the size of *DS-3DTiles-Tmp* is 7.3 times smaller than *DS-CityGML* and 1.4 times smaller than *DS-3DTiles*. The difference between the CityGML based representation (*DS-CityGML*) and the 3D Tiles based representations (*DS-3DTiles* and *DS-3DTiles-Tmp*) has two main explanations. First, *DS-3DTiles* and *DS-3DTiles-Tmp* do not store the hierarchical structure of the data present in *DS-CityGML*. It could however be added using the *batch_table_hierarchy* extension of 3D Tiles. Secondly, the representation of the data proposed by 3D Tiles and based on JSON and binary encoding is lighter than the xml-based representation CityGML. One can also note that while the size of the 2012 vintage of *DS-CityGML* is bigger than the 2015 vintage, it is the opposite for *DS-3DTiles*. This is due to the fact that the 2009 and 2012 vintages of *DS-CityGML* are stored in CityGML version 1.0, while the 2015 vintage is

stored in CityGML version 2.0. However, the version of 3D Tiles is the same for all the vintages of *DS-3DTiles*. In addition, the 2015 vintage represents buildings at a higher level of detail than the 2009 and 2012 vintages. Therefore, the size of the 2015 vintage is bigger than the size of the 2012 vintage in *DS-3DTiles*.

Comparing the sizes of *DS-3DTiles* and *DS-3DTiles-Tmp* shows one advantage of using the temporal extension proposed in this chapter. The model proposed for our extension indeed enables a significant gain in size while allowing the storage of more information describing the evolution of the city (periods and transactions between features in this case) in comparison with CityGML and 3D Tiles. This size gain is correlated with the reduction of the number of stored buildings. It indeed falls from 53951 to 36975 between *DS-3DTiles* and *DS-3DTiles-Tmp* (which represents a ratio of 1.5). It is explained by the fact that a building having a persistent state in more than one timestamp is stored multiple times in *DS-3DTiles* but only one time in *DS-3DTiles-Tmp*. For instance, a building which is in the same state in 2009, 2012 and 2015 is stored three times in *DS-CityGML* and *DS-3DTiles* (once in 2009, once in 2012 and once in 2015) and only one time in *DS-3DTiles-Tmp* (with the period [2009; 2015]).

This memory gain is a great improvement, as reducing the size of the dataset makes it possible both to reduce the network transmission time and the memory footprint for the client, which are limiting factors for achieving interactive spatio-temporal visualization and navigation. In the next section, we evaluate this gain in interactivity for spatio-temporal navigation.

These results can be reproduced with the following procedure : <https://archive.softwareheritage.org/swh:1:dir:aa7e1acfe0acd9e9891f42fb52d13be6c0250f36;origin=https://github.com/VCityTeam/UD-Reproducibility>

Spatio-temporal navigation evaluation

We recorded the time for loading, rendering and navigating in *DS-3DTiles* and *DS-3DTiles-Tmp* to evaluate the interactivity of the spatio-temporal navigation. To this end, they have been visualized in *UD-Viz* (presented in section 3.3.1). The following experiments have been conducted with an Intel Core i7-4790K CPU @ 4.00GHZ and with 32GB of RAM. The data have been delivered using a local web server and visualized with a Firefox 67.0 web browser.

Table 3.2 presents the mean time as well as the standard deviation for loading and rendering *DS-3DTiles* and *DS-3DTiles-Tmp*, measured on 10 samples. It shows

that the time for loading and rendering *DS-3DTiles-Tmp* is lower than the time for loading and rendering all snapshots (2009, 2012 and 2015) of *DS-3DTiles* (3D Tiles). Moreover, *DS-3DTiles-Tmp* stores additional thematic information about the evolution of features in time (transactions and features' period) in comparison with *DS-3DTiles*.

Dataset	Mean loading and rendering time (seconds)	Standard deviation
DS-3DTiles	2009	1.4
	2012	1.4
	2015	1.9
	Total	4.7
DS-3DTiles-Tmp	3	0.04

Table 3.2.: Time for loading and rendering *DS-3DTiles* and *DS-3DTiles-Tmp*

Figure 3.8 presents a comparison of the animation time when navigating between timestamps with *DS-3DTiles* (3D Tiles) and *DS-3DTiles-Tmp* (3D Tiles temporal extension). Each box represents a state at a given date indicated inside the box (\emptyset indicating that nothing is displayed). The arrows express a change of state. The mean loading and rendering time (seconds) are respectively in black for *DS-3DTiles* and in green for *DS-3DTiles-Tmp* (respectively indicated as xx seconds / xx seconds). The temporal extension introduces a small overhead for displaying the first state (going from nothing to 2009 or 2012 or 2015). However, navigation in time is significantly improved since it only takes 0.1 seconds to switch from one state to another instead of 1.4 and 1.9 seconds with *DS-3DTiles*.

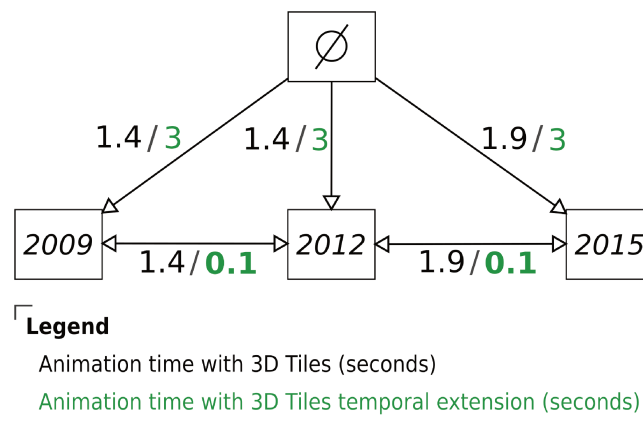


Figure 3.8.: Animation time comparison of *DS-3DTiles* and *DS-3DTiles-Tmp*.

In the current implementation, the data is indexed according to a *kd-tree*. We believe that implementing a spatio-temporal indexing method, such as an *HR-Tree* [YP01] for instance, may reduce the time for loading and rendering *DS-3DTiles-Tmp*, especially for displaying the first state (from nothing displayed to a first state). Such an indexing method would indeed allow to better organize the features along the temporal axis and therefore reduce the number of features that are transmitted to the client for the first display state.

Finally, our temporal extension allows to access information between the three temporal states of *DS-3DTiles* (2009, 2012 and 2015). This idea is depicted in figure 3.9 where we can see that the temporal extension allows to navigate in transitory states between two temporal snapshots. The measured time on this figure show that this navigation can be done at a fraction of the cost than with classic 3D Tiles. Therefore, our extension allows to greatly enhance navigation in time.

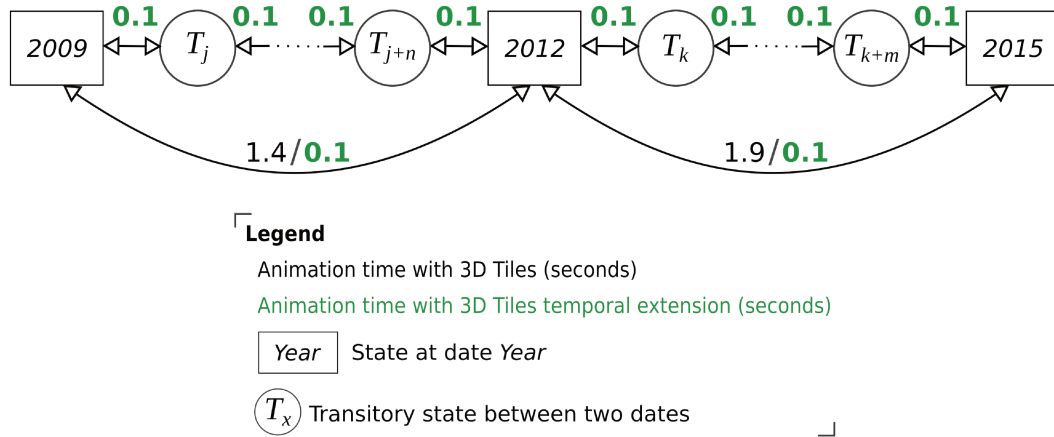


Figure 3.9.: Temporal navigation comparison between 3D Tiles and 3D Tiles with temporal extension.

These results can be reproduced with the following procedure : <https://archive.softwareheritage.org/swh:1:dir:b444ef8a41da04d5f9ff4a46ebd3ecff0f485e77;origin=https://github.com/VCityTeam/UD-Reproducibility>

3.3.3 Visualize urban evolution in 3D and on the web

In this section, we propose visualization rules for displaying time-evolving 3D city models represented in 3D Tiles extended with *3DTiles_temporal*. The purpose of these visualization rules are to highlight changes in the city to help understanding urban evolution. Our proposition is to represent features' known states in a reference color (light gray in this example) and to showcase transactions between these states.

Generally, transactions span for a certain amount of time and we do not have access to the geometry of the feature(s) concerned by the transaction during this amount of time. Therefore, we propose the following display rule for transactions: during the first half of the transaction, the geometry of the **previous known state** is displayed. During the second half of a transaction, the geometry of the **following known state** is displayed. The type of transaction (*creation, modification, etc.*) determines the color in which the geometry is displayed. In this example, only *creations, modifications* and *demolitions* are managed. However, other transactions could easily be added by following the same rules. *Creations* are in green, *modifications* are in yellow and *demolitions* are in red. Finally, the opacity varies during the time of the transaction in the way that it is equal to 1 at the beginning and at the end of the transaction and to 0 at the half duration of the transaction. Between these timestamps, it decreases on the first half of the transaction (from 1 to 0) and increases during the second half of the transaction (from 0 to 1). Figure 3.10 illustrates this proposition on three types of transactions.

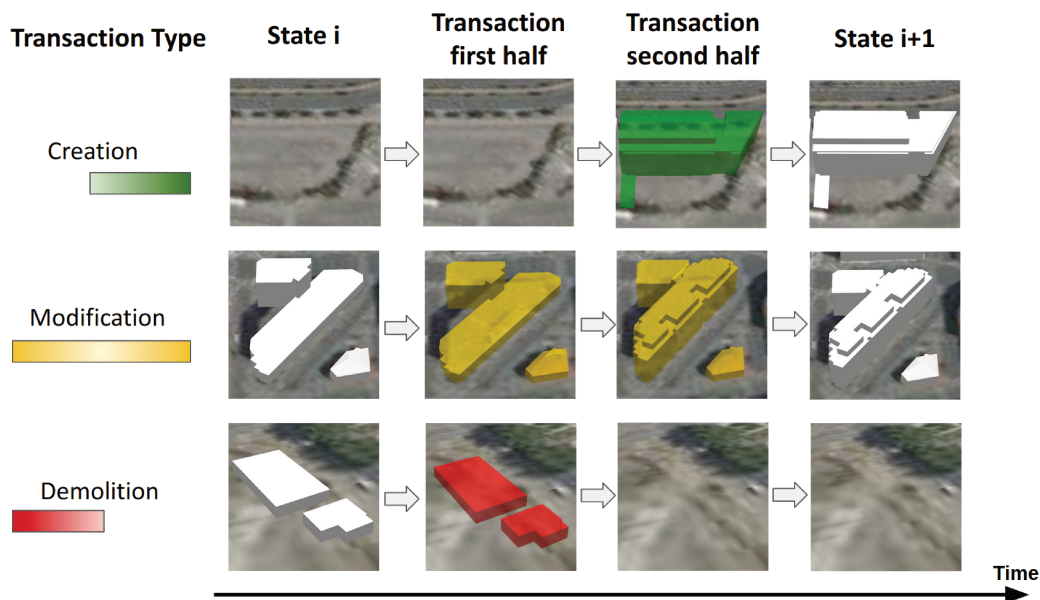


Figure 3.10.: Example of visual representation of buildings known states (state i and state $i+1$) and of transactions between these states. States are in gray, creations in green, modifications in yellow and demolitions in red.

These visualization rules have been implemented in *UD-Viz* (described in section 3.3.1). This implementation also allows users to navigate freely in space (3D scene) and in time (with a time slider). Figure 3.11 shows two screenshots, representing the visualization of a part of *DS-3DTiles-Tmp* (one district of the city) in 2013 (on the left side) and in 2014 (on the right side).



Figure 3.11.: Screenshots showing the evolution of a district of the city of Lyon (in 2013 on the left side and in 2014 on the right side) visualized in *UD-Viz* and using 3D Tiles extended with *3DTiles_temporal*.

In figure 3.11, we can clearly identify the changes occurring at these two dates. In particular, we can see buildings that are being destroyed (in red), modified (in yellow) and constructed (in green). Figure 3.12 shows a visualization of the full city of Lyon in 2014. Visualizing the evolution of the city at this scale can be very useful to detect areas where a lot of changes happen for instance. One can then zoom to these areas to see more details about the changes (such as in figure 3.11).



Figure 3.12.: Screenshot of the visualization of the city of Lyon in 2014 in *UD-Viz*, using 3D Tiles extended with *3DTiles_temporal*.

In this section, we showed a possible use case of the extension we proposed in this chapter. Other visualization of the data may be implemented to suit specific

user needs since it is independent from the data modelling part. However, this visualization can be useful to understand and share urban evolution which is of big interest for applications such as cultural heritage or urban planning.

These results can be reproduced with the following procedure : <https://archive.softwareheritage.org/swh:1:dir:424c7db8cb2435ccfb52f1dbed124f1685d8dcc0;origin=https://github.com/VCityTeam/UD-Reproducibility/>

3.4 Discussion

In this chapter, we proposed several contributions for time-evolving 3D city models visualization on the web. First, we proposed **Gen3DGeo**, a generic conceptual model for delivering 3D geographic features for web visualization based on standard formats (3D Tiles and I3S). This model contributes to the geospatial community with a conceptual and harmonized view of these standards, also aligning them with propositions from ISO [Int08]. Then, we proposed *Gen4DCity*, a conceptual model for time-evolving 3D city models visualization on the web. This model contains a formalization of the temporal dimension of cities, extending the work of Renolen [Ren00] and Chaturvedi et al. [Cha+17] which is more flexible and aligns typologies of changes. We also formalized 3D Tiles at logical level and integrated the temporal dimension in *Logic4DCity* and proposed a technical specification of the 3D Tiles temporal extension (*3DTiles_temporal*). After that, we provided an open source implementation of this extension. This implementation allowed to evaluate the interactivity of the spatio-temporal navigation in large-scale time-evolving 3D city models. In particular, we demonstrated that our contribution allows to significantly improve temporal navigation in comparison with a snapshot based representation of the city. Finally, we proposed rules of visualization for highlighting urban evolution and presented an example of visualization of the city of Lyon, France. This implementation and evaluation are provided with detailed notes available online and allowing to reproduce the results.

These contributions open potentials for new research and developments. First, a specification of *Gen4DCity* to the I3S standard format may be studied in more details. Secondly, we believe that spatio-temporal navigation performances may be improved with the implementation of other data indexing methods such as spatio-temporal indexing methods [The+98; Had+02; Mok+03]. We for instance expect Historical R-Trees in their enhanced version (HR+-trees) [YP01] to be an interesting first lead to be evaluated since the indexing of the data has similarities with the

3DTiles_temporal extension. In addition, they perform well on time-stamp queries which are of particular interest in our use case. Such a spatio-temporal indexing method could allow to implement a promising approach based on delivering the temporal evolution as a progressive stream. Thirdly, we would like to propose an example using all the concepts proposed in the formalization of the temporal dimension (i.e. *Versions* and *VersionTransitions*). We are confident that this may happen in the future since 3D city models datasets are now being produced on a regular basis and their use for diverse applications is increasing. Therefore, more data will become available and representing and analysing the evolution of 3D city models will be of particular interest to exploit this data.

In the next chapter, we go further in representing the city and its evolution with contributions allowing to integrate multimedia documents to time-evolving 3D city models. These contributions will allow to prove past states of cities and why it evolved in a certain way. In particular, it permits to integrate sources and proofs regarding these states and evolution.

Multimedia documents and time-evolving 3D city models: integration and navigation

Contents

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In this chapter, we propose contributions to integrate and navigate multimedia documents and time-evolving 3D city models. In this objective, we propose the following contributions and outline:

- **Developing a generic conceptual model** for linking features (*GenLinkable* model) (section 4.1)
- **Specifying** this model for **multimedia documents** and **time-evolving 3D city models** integration (*Gen4DCity-Doc*, extending *Gen4DCity*) (section 4.2)
- **Implementing** a proof of concept for multimedia documents and 3D city models navigation, enhancing the prototype presented in chapter 3 and **documenting** the procedures to ensure **reproducibility** (section 4.3)

We finish this chapter with a discussion on the contributions and on potential future leads (section 4.4).

4.1 General concepts

We introduce two concepts for features integration: **Linkable Feature** and **Link** (specifying the concepts proposed in [Pap+94]).

Definition 1. Linkable Feature. A linkable feature is an abstract data type allowing the operation “*being linked to*”.

Definition 2. Link. A link is an entity describing the relation between any two linkable features. A link is not oriented, i.e. it expresses a two-way association.

A conceptual model describing these concepts and their relation is presented in figure 4.1. We name this model **GenLinkable**.

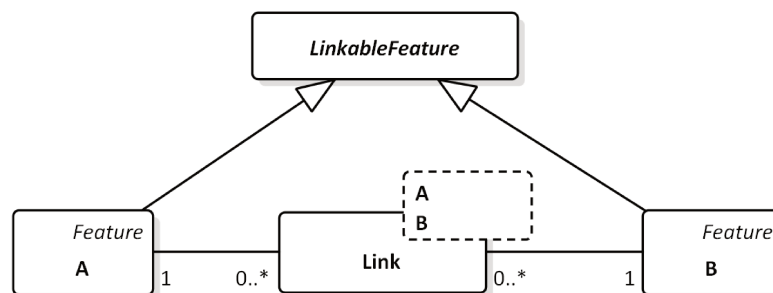


Figure 4.1.: **GenLinkable:** Conceptual model for linking features.

We define the *Link* as a template class¹ with two template parameters : *A* and *B*. This notation allows to express that a *Link* is between two entities *A* and *B* which are template parameters that can be substituted by other entities. In this case, they can be substituted to specify which entities can be linked (e.g. geographic features with multimedia documents). This model choice is particularly useful to constrain the possibilities of the types of features that can be linked. For instance, let's take an information system that manages sensor data streams, multimedia documents and 3D city models. This model for instance allows to limit linkage to the 3D city model's features and to multimedia documents. We give an example of binding in section 4.2. To constrain this model to geospatial information, *A* and *B* are features.

Linkable Feature is defined as an abstract class allowing the operation “being linked to”. A *Linkable Feature* may be associated with 0 to many *Links*, allowing to manage multiple relations between features. *A* and *B* are *Linkable Features*.

We propose a logical model of *Link* in figure 4.2.

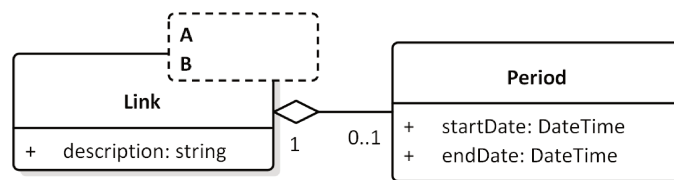


Figure 4.2.: Logical model of *Link*.

The *Link* has a *description* attribute and a *period*. *Description* stores thematic information while *period* stores temporal information (its period of existence in time). The link's *period* may indeed be different than the ones of *A* and *B*. For instance, a multimedia document might refer a geographic feature only for a part of its (the geographic feature) period. For consistency, we restrict the *Link*'s period to the following. Let's define two linkable features \mathcal{LF}_1 and \mathcal{LF}_2 , respectively having the periods $\mathcal{T}_{\mathcal{LF}_1}$ and $\mathcal{T}_{\mathcal{LF}_2}$. Let's define \mathcal{L} a link with the period $\mathcal{T}_{\mathcal{L}}$. If \mathcal{L} is a link between \mathcal{LF}_1 and \mathcal{LF}_2 , then $\mathcal{T}_{\mathcal{L}} \in \mathcal{T}_{\mathcal{LF}_1} \cap \mathcal{T}_{\mathcal{LF}_2}$.

Figure 4.2 describes generic attributes of *Link*. Since it is a template class, classes bound to *Link* may have other attributes (e.g. specific to one's application and to the features that are linked). A typical use case may be to add a *spatial dimension* to the link, which can be useful when the link must be visualized in an end-user application.

¹<https://www.uml-diagrams.org/template.html>

This model propose top-level concepts, providing a way to integrate features without interfering with their representation in their respective formats. In the next section, we specify this model for time-evolving 3D city models and multimedia documents integration.

4.2 Time-evolving 3D city models and multimedia documents integration

Figure 4.3 presents **Gen4DCity-Doc**: a generic conceptual model for time-evolving 3D city models and multimedia documents integration. This model extends *Gen4DCity* (from figure 3.2) with *GenLinkable* (from figure 4.1) and with *Multimedia Documents*.

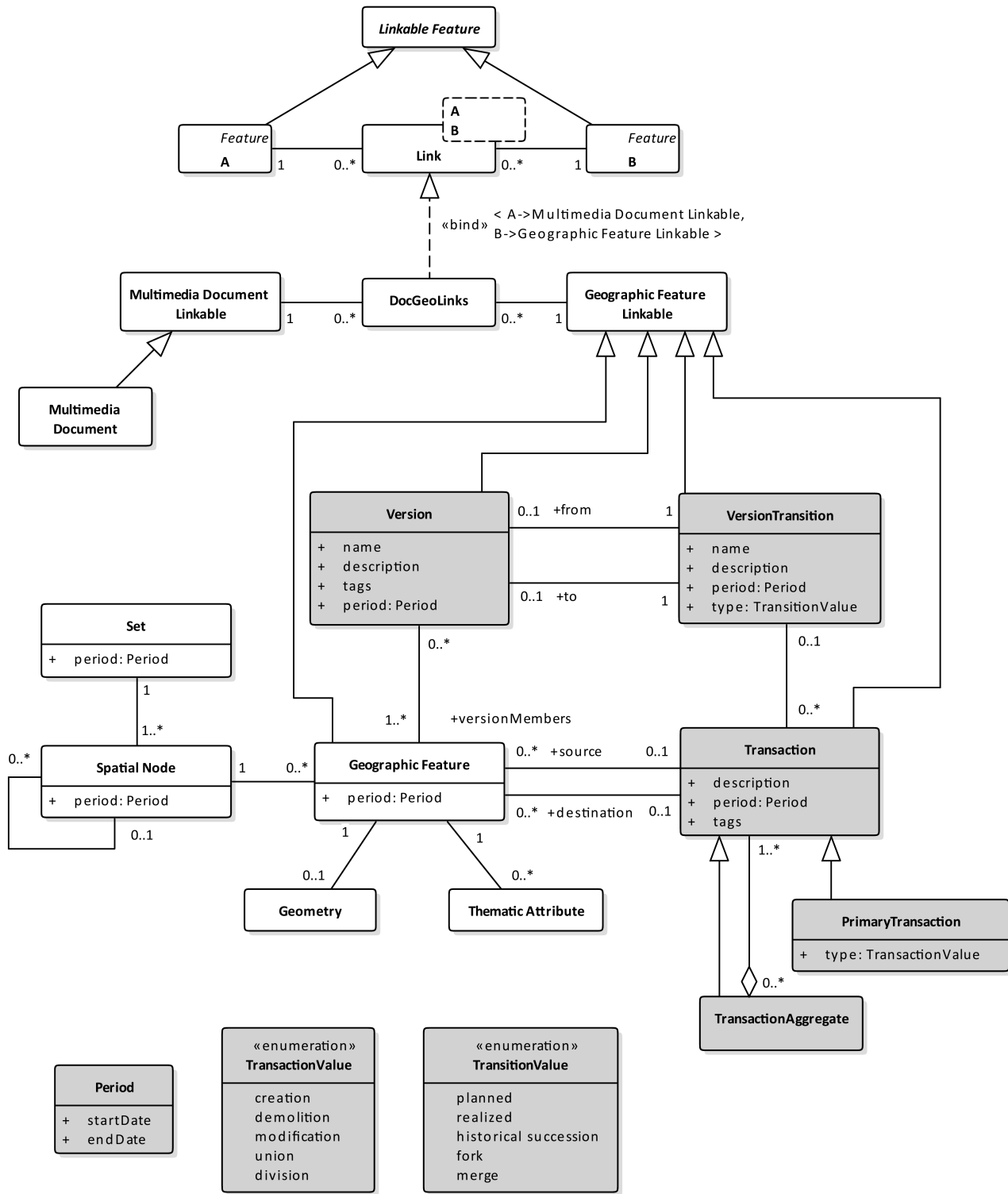


Figure 4.3.: Gen4DCity-Doc: Generic conceptual model integrating time-evolving 3D city models and multimedia documents.

DocGeoLinks is bound to *Link*. The template parameter *A* is substituted by *Multimedia Document Linkable* and *B* by *Geographic Feature Linkable*. These classes respectively allow to express which concepts from the multimedia documents model and which concepts from *Gen4DCity* are linkable. We represent the multimedia documents model by the *Multimedia Document* entity. This entity is specified in section 4.3. Several classes from *Gen4DCity* become linkable. First, *Geographic Features* (e.g. buildings, bridges, etc.) can be linked with *Multimedia Documents*, which is a common need for many documents such as pictures. Another typical need is to allow the integration of *Multimedia Documents* and *Transactions*. Documents can indeed help to give elements of proofs regarding how geographic features evolves in time for instance. Figure 4.4 shows an example of links between multimedia documents, geographic features and transaction.

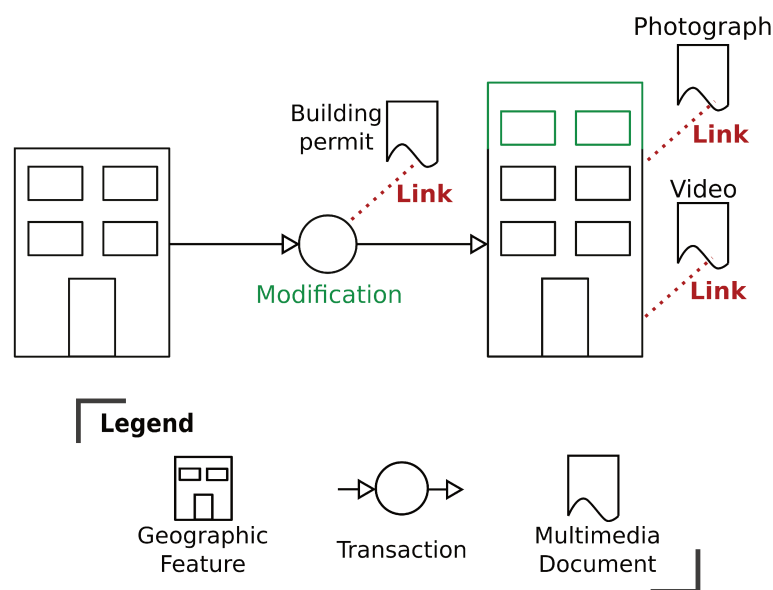


Figure 4.4.: Example of links between multimedia documents and geographic features and transaction.

Similarly, *Version* and *VersionTransition* can be linked with *Multimedia Documents*. Let us consider a version depicting the state of a city district before a renovation is undertaken. One can then link building permits (which are multimedia documents) to this version. Let us consider several other versions of this project and version transitions between these versions. Multimedia documents related to changes that are supposed to take place between these two versions can also be linked to these version transitions.

4.3 Implementation

The proposed implementation focuses on multimedia documents and city objects integration as a first step. Figure 4.5 is a logical model showing the scope of the implementation and the relation between the implemented classes and *Gen4DCity-Doc* (figure 4.3).

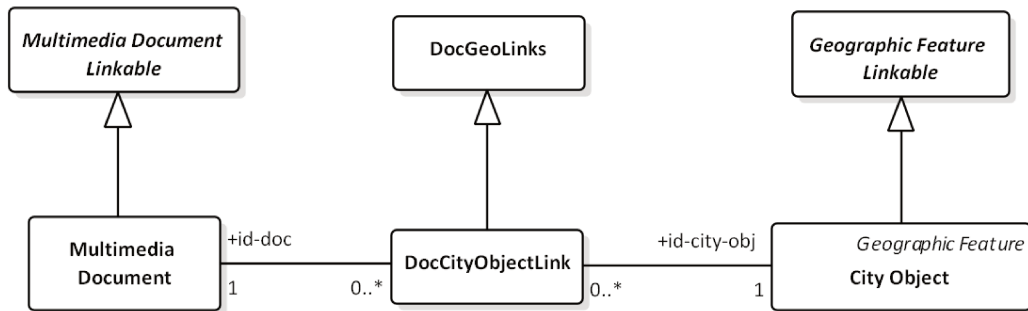


Figure 4.5.: Logical model of the implemented link between multimedia documents and city objects.

City object is a *Geographic Feature*. *DocCityObjectLink* is the entity describing links between *Multimedia Document* and *City Object*. A physical model is presented in Appendix B.

The models proposed in this chapter and this implementation are modular. Therefore, the same process could be applied to other features (e.g. transactions). In section 4.3.1, we present the evolution of the architecture of our prototype to integrate multimedia documents and links. Then, we demonstrate how the propositions of this chapter enhance navigation in multimedia documents and 3D city models.

4.3.1 Software architecture

We enhanced the open source web prototype proposed in section 3.3.1 with an implementation of the propositions of this chapter. The updated software architecture is presented in figure 4.6. The components that have been added are in light blue. Two modules have been added to *UD-Viz*² : *Documents* and *Links*. *Documents* and *Links* modules are interfaced with corresponding REST APIs provided by *UD-Serv*³.

²<https://archive.softwareheritage.org/swh:1:rev:b5a523825862a3f2dd440c2922485cdd30009834;origin=https://github.com/VCityTeam/UD-Viz/>

³<https://archive.softwareheritage.org/swh:1:rev:c89553bf9098246f59ec68df2b12501f698aff77;origin=https://github.com/VCityTeam/UD-Serv/>

UD-Serv is a collection of server-side tools for converting, analyzing and exposing urban data. In particular, it contains the *Enhanced City* module which exposes APIs for realizing *CRUD* (Create, Read, Update, Delete) operations on multimedia documents and links. City objects are stored in a *3DCityDB* database (as explained in Appendix B) and converted into the 3D Tiles format for visualization with the *City Tiler* process of *py3dTiles* (presented in section 3.3.1). The 3D Tiles dataset is delivered by a 3D Tiles HTTP Server. In *UD-Viz*, city objects are still managed by the *City Object* module.

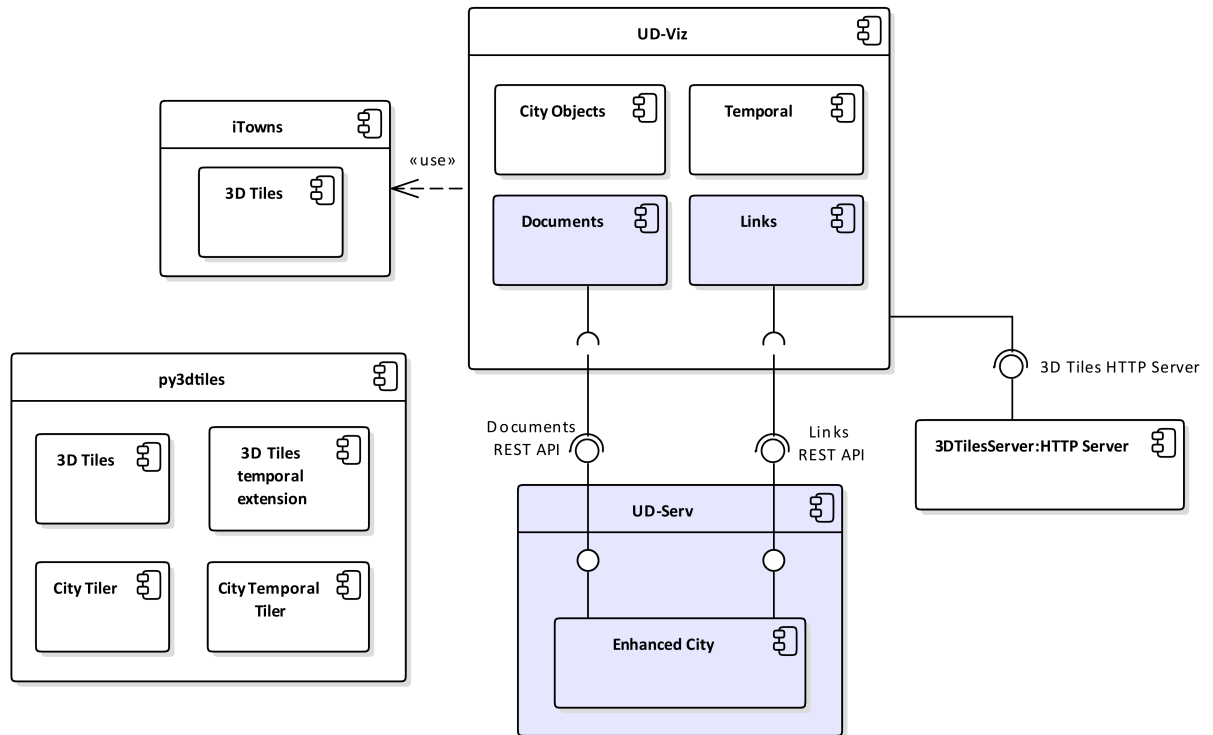


Figure 4.6.: Software architecture of our web based prototype, enhancing the software architecture of figure 3.7 with the implementation of the propositions of this chapter. The new software components implementing the propositions of this chapter are depicted in blue.

4.3.2 Navigate in a documented 3D city on the web

The 3D city model used for the examples of this section represents the city of Lyon plus two surrounding cities (Villeurbanne and Bron) (73 km^2 in total) in 2015. The multimedia documents have been imported manually from the database of the

“cultural heritage and general inventory” department of the *Auvergne-Rhône-Alpes* region (France) (that can be consulted online⁴).

Our prototype makes it possible to navigate geolocated 3D city objects and multimedia documents in a separated or in an integrated way. An overview of its interface is presented in figure 4.7. Two windows allow users to navigate multimedia documents. The *Document - Navigator* window on the upper-left corner lists available multimedia documents about the city, allows to filter them (e.g. according to their attributes) and to create new ones. One can select a multimedia document from this window to see its details in the *Document - Inspector* window in the upper-right corner. The 3D city is displayed in the background. Users can navigate freely in the 3D scene and select a city object (highlighted in blue) to access its thematic information in the *City Objects* window on the lower-left corner.

The links of a multimedia document and of a city object are respectively stored in the *Document - Inspector* window and in the *City Objects* window. In this way, a user which is consulting a document in the *Document - Inspector* window can directly access linked city objects. Similarly, a user consulting a city object from the 3D scene can access linked documents. New links can also be created from these windows.

⁴<https://patrimoine.auvergnerhonealpes.fr/>

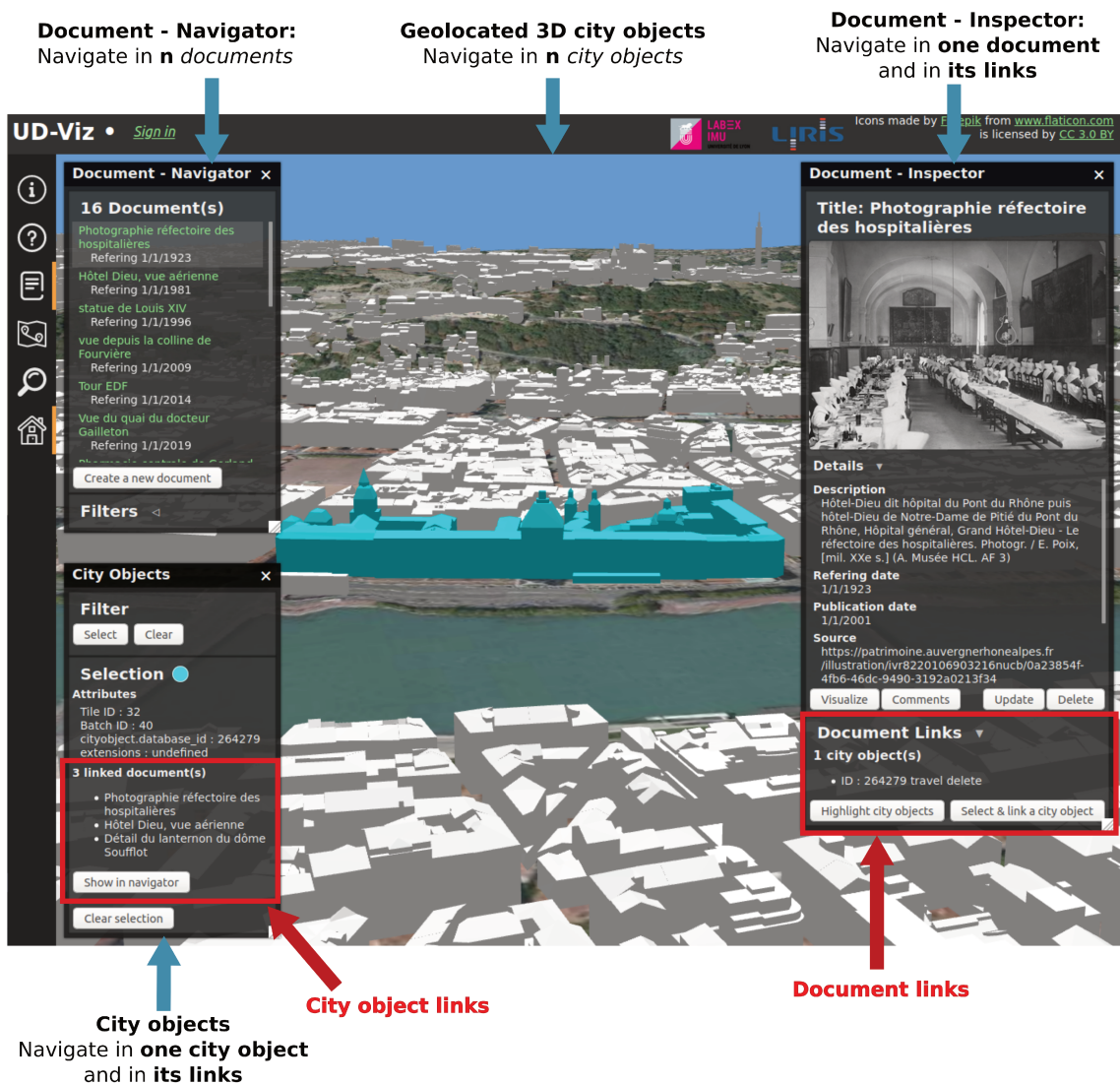


Figure 4.7.: Interface and main components of the prototype for linking and navigating multimedia documents and city objects.

One technical question concerned the visual representation of the link in the 3D scene since it does not have an intrinsic geometry. One possibility is to assign it one. Previous work have been undertaken in that direction [Cha+16], where multimedia documents are displayed as billboards placed over the city element they reference and the link is represented by a line between a multimedia document and a city object. However, this approach still leaves open questions such as: *How to display a big quantity of documents on a screen with a limited size? How to place a document when it has multiple links?* Another possibility is to highlight linked city objects and multimedia documents. Highlighting objects for geovisualization is a well studied subject [Rob11; Tra13] and several possibilities can be implemented depending on

the use case. As a first step, we chose to highlight city objects by changing their color and to showcase documents by displaying them in the *Document - Navigator* and *Document - Inspector* window. Colors were chosen arbitrarily. We may use color palettes (e.g. ColorBrewer⁵) in further developments.

Links allow to navigate from documents to city objects and from city objects to documents. In addition, they allow to associate documents that cannot be integrated to city objects at the visual level. Figure 4.7 shows such an example. A document representing a scene happening in the interior of a building is displayed in the *Document - Navigator*. To **navigate from this document to city objects**, a user can choose to highlight city objects linked to this document with the *highlight city objects* button in the *Document - Inspector window* (see figure 4.7). This will highlight linked city objects in dark blue. Then, a user can select one of these highlighted city objects from the 3D scene. The selected city object is displayed in light blue in the 3D scene and its details and links are displayed in the *City Objects* window (such as in figure 4.7). Then, a user can **navigate from this city object to documents** by clicking on the *Show in navigator* button of the *City Objects* window (see *city object links* on the lower-left corner of figure 4.7). This will restrict the list of documents of the *Document - Navigator* to the one linked to this city object (three in this case). Then, a user can choose one of this documents to display it in the *Document - Inspector* window and continue navigating from this document to other linked city objects.

Beyond navigation, it is also possible to extract and display quantitative information about documents, city objects and links. From our interface, it is possible to display such quantitative information by setting filters from the *City Object* window. These first filters are given as examples and more complex ones could be implemented. In particular, specific filters could be defined with cultural heritage experts or researchers in urban heritage for instance. Figure 4.8 shows an example of such a filter which highlights the city objects with at least one linked document.

⁵<http://colorbrewer2.org/>

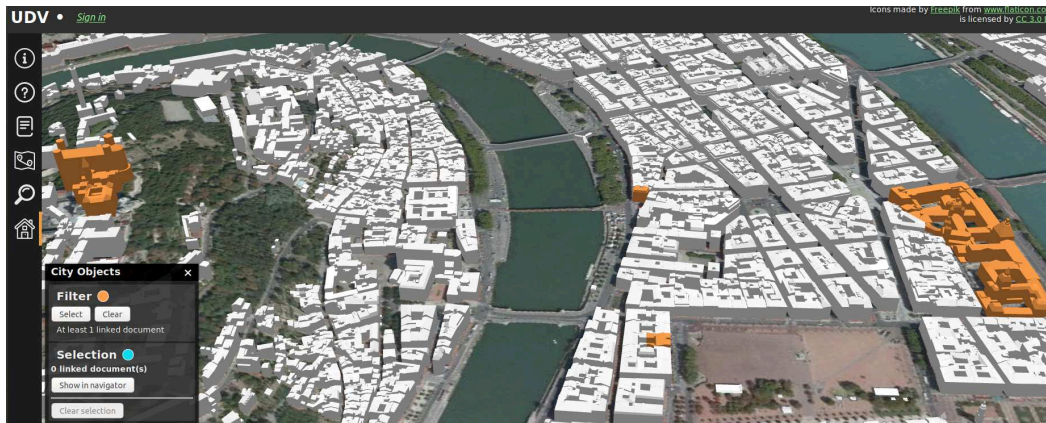


Figure 4.8.: City objects filters example. City objects having at least one linked document are displayed in orange in the 3D scene.

These results can be reproduced with the following procedure : <https://archive.softwareheritage.org/swh:1:dir:247366dc021f2b61a3d8abf6bc07be35b4e5d734;origin=https://github.com/VCityTeam/UD-Reproducibility/>⁶

4.4 Discussion

In this chapter, we proposed a two-step approach for integrating time-evolving 3D city models and multimedia documents for navigation and visualization on the web. First, we provided a generic conceptual model for linking **features** (**GenLinkable** model). This model has the advantage of being non intrusive in the features' models (e.g. it allows multimedia documents and city objects linkage without the need to modify their individual data models) and is generic to all types of features. Secondly, we specified this model to integrate time-evolving 3D city models and multimedia documents (**Gen4DCity-Doc** model). This model enhances *Gen4DCity* with multimedia documents. Finally, we proposed an open source implementation for 3D city objects and multimedia documents integration and navigation by enhancing the prototype previously introduced and provided an online documentation to ensure **reproducibility**.

This prototype has been tested by urban heritage experts. First elements of evaluation show that beyond possible ergonomic enhancement, this proposition enhance navigation and may help experts and non experts to discover cultural heritage and

⁶The demonstration installed by following these reproducibility notes currently do not embed the documents used in this section. However, one can add its own multimedia documents and try the navigation possibilities.

associated documentation. In addition, we discussed more evolved filters that could be useful to them, such as: *Which city objects have at least n linked documents ?* *What are the city objects with the most linked documents ?* . The first query may help navigation by allowing a user to know where to look for documentation. The second query may help to identify which city objects are well documented. In the context of a participatory tool (which is was one objective of the Fab-Pat project), it may be really useful for detecting famous city objects or particular events that happened in relation to a city object. In the context of cultural heritage, crossing such information with the list of city objects already considered as cultural heritage by institutions can help detect city objects that might be (or need to be) considered as cultural heritage in the future.

In the future, our generic proposition (*GenLinkable*) could be enhanced to permit linkage of subsets of features. For instance, say that you have a city model containing a building which is decomposed in walls and a roof. The building, the walls and the roof are features. Let us consider a multimedia document that needs to be related to a fragment of one of the walls (e.g. for specifying renovation work to do on this fragment of wall). It may not be possible to create a new feature representing the wall fragment in the city model to link a document to it. In this case, the way to go with the current proposition would be to link the document to the wall and to specify in the description attribute of the link that it refers a fragment of the wall. However, this is not satisfying since it may be hard to clearly define the wall fragment in the description attribute of the link. Similar examples could be found with multimedia document referring to thematic attributes (e.g. to the owner of a building). Therefore, it would be useful to be able to link subsets of features. One interesting lead to do so may be to extend and specify the *Anchor* concept proposed by Papa et al. [Pap+94]. In their context, this concept indeed allows to refer specific parts of a document (we remind that their objective is to develop a multimedia information system and to allow linkage of multimedia documents). However, not many details are given about this concept and about how it has been implemented. In addition their scope is limited to multimedia documents while we aim at linking features that can have geometric, temporal and thematic dimensions. Therefore this concept would need to be extended to manage subsets of features in one or more of these dimensions. Therefore, further studies will need to be carried out to integrate this concept to *GenLinkable*.

Implementation overview: Process, Architecture and Reproducibility

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In this chapter, we provide an overview of the implementation have been realized in this thesis. We present the following contributions and outline:

- A **process computing time-evolving 3D city models** in the 3D Tiles with *3DTiles_temporal* extension from time-stamped 3D city model, contributing to the propositions of chapter 3. We detail the different steps of this process, the difficulties encountered and how we overcame them. (section 5.1)
- The 4-tier architecture of UD-SV¹ (Urban Data Services and Visualization) that we contributed to design and implement in this thesis (section 5.2)
- Our approach for interoperable and reusable systems and for reproducible experiments (section 5.3)

5.1 Time-evolving 3D city models creation process

The contributions of chapter 3 led us to propose a process for computing time-evolving 3D city models. The need for this process stem from the lack of available time-evolving 3D city models (i.e. 3D city models integrating the temporal dimension) and from the need to evaluate our contributions from chapter 3 on large datasets. With the development of acquisition techniques, 3D city models are regularly produced. Some of these represent the same spatial areas but at different dates. For instance, the city of Lyon has produced and made openly available a 3D city model of its agglomeration every three years since 2009. These time-stamped 3D city models constitute a good data source to create time-evolving 3D city models.

Figure 5.1 present an activity diagram describing the process for creating a time-evolving 3D city model in 3D Tiles with the *3DTILES_temporal* extension from time-stamped 3D city models (vintages) in the CityGML format. This process is based on three main steps:

- **Step 1: Improving data quality.** As we will see in section 5.1.1, working from data acquired from the real world can be challenging and corrective steps must be realized before any other processing step.
- **Step 2: Detecting changes.** This step is described in section 5.1.2 and allows to detect geometric (e.g. modification of the geometry of a roof) and thematic changes (e.g. grouping together two different buildings).

¹<https://archive.softwareheritage.org/swh:1:rev:ba6573d19a83fc75bf8fd546f43c31696f65c1a7;origin=https://github.com/VCityTeam/UD-SV/>

- **Step 3: Aggregating into a time-evolving 3D city model.** This step consists in aggregating the vintages in one time-evolving 3D city models containing spatio-temporal city objects and transactions between them. It is described in section 5.1.3.

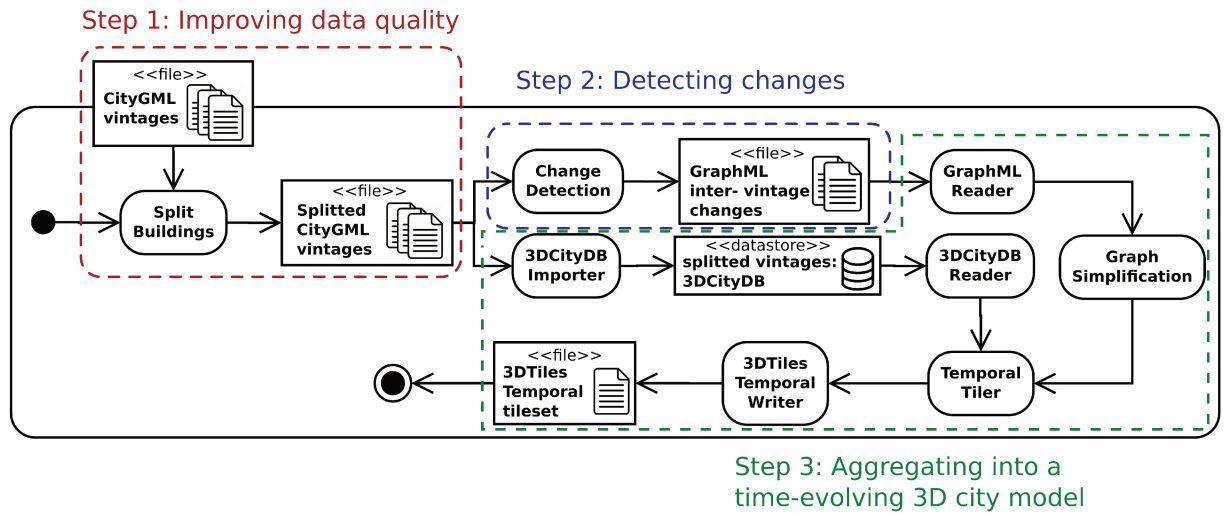


Figure 5.1.: Activity diagram of the process to create a time-evolving 3D city model in 3D Tiles with the *3DTiles_temporal* extension from time-stamped 3D city models in the CityGML format.

These processing steps are spread over several software components (see Table 5.1).

Software component	Action
3DUSE	Split Buildings
	Change Detection
3DCityDB	3DCityDB Importer
py3dtiles	GraphML Reader
	3DCityDB Reader
	Graph Simplification
	Temporal Tiler
	3D Tiles temporal Writer

Table 5.1.: Actions of the activity diagram of figure 5.1 and the software components that realizes them.

This process has been tested on the 2009, 2012 and 2015 vintages of the city of Lyon since it is currently the only large-scale 3D city model openly available at different dates in the CityGML format. In addition, we focused on buildings as a first step.

However, this process has been designed in a modular and generic way to allow its usage for other city objects (e.g. bridges) and other datasets (e.g. representing other cities).

5.1.1 Step 1: Improving data quality

The Grand Lyon provide no information about the quality of the data it provides. For instance, there is nothing on geometric precision of the data. In addition, the acquisition and data creation processes are not detailed which does not allow to evaluate the quality of the input data. While working with this data, we found out many quality issues. We classify them and propose methods to overcome them. Some of these issues may be specific to the data of the city of Lyon. However, it illustrates the difficulties that can arise when working with open large-scale datasets acquired from the real world. In addition, we believe it may be useful for future work with this data or with similar datasets from other cities. This analysis has been summarized for readability reason but more examples are provided online².

We found quality issues of two types: **intra-vintage** (related to one time-stamped 3D city model) and **inter-vintages** (related to inconsistencies between several time-stamped 3D city models).

Intra-vintage quality issues

First, there is **encoding errors**. Some files are corrupted due to errors such as xml tags not closed, invalid number instead of geometric coordinate, etc. Other files have wrongly specified CityGML version in their heading. The CityGML version indeed changes among files describing one vintage and do not always reflect the actual version used in the file. For instance, some files of the 2009 vintage are indicated as being encoded in version 1.0 and others in version 2.0, while they are in fact all written according to version 1.0. These few issues have been corrected on a case to case basis (at least to make corrupted files usable) and a feedback is continuously given to the “Grand Lyon” (who produces these data).

Secondly, there is **undocumented thematic data** which makes them difficult to use. A lot of thematic attributes are indeed provided as CityGML *generic attributes* (e.g. “address”, “zminroof”, etc.), without any documentation explaining what they stand

²<https://archive.softwareheritage.org/swh:1:dir:65963235ff00a37088b1b93283a896f4445c0cf4;origin=https://github.com/VCityTeam/UD-SV/>

for. In addition, some of them could have been defined with attributes intended for this purpose. In our case, we considered them unusable and dropped them.

Finally, there is **non quantified geometric inaccuracies**, which complicates vintages comparison for change detection (second step). In this context, it becomes difficult to define the threshold between two different geometries.

Inter-vintages quality issues

In addition to these intra-vintages issues, there is also some inter-vintages inconsistencies. First, there is **labeling inconsistencies** between vintages. A building that is in the same state in 2009 and in 2012 is labeled with different identifiers in the two vintages and no attribute allows to know related them. Therefore, we cannot relate on identifiers nor attributes to compare buildings between vintages.

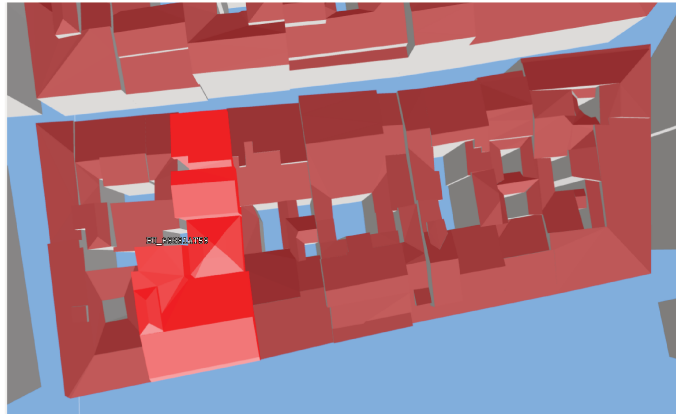
Secondly, there is **thematic structuring inconsistencies** across vintages. There is no logical criteria for structuring the 2009 and 2012 vintages, and the structuring is different between these two vintages. The 2015 vintage is structured according to the cadastral plan. Figure 5.2 shows a visualization of a borough of Lyon 2009 vintage. A building object as defined in the CityGML file, and corresponding to several buildings in the real world, is highlighted in red.



Figure 5.2.: Screenshot of a borough of Lyon 2009 vintage. In red, a building as defined in the CityGML file, which corresponds to multiple buildings in the real world.

Figure 5.3 presents a 3D visualization and the footprints of a building block of Lyon 2015 vintage.

3D view



2D footprints

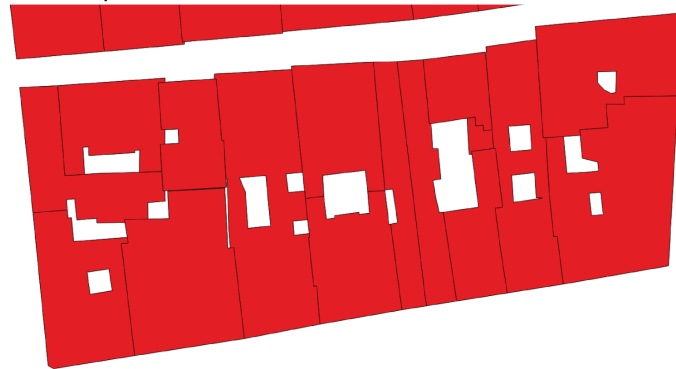


Figure 5.3.: Example of structuration of the 2015 vintage of the city of Lyon according to the cadastral plan. On the top, we present a 3D view of a building block. On the image on the bottom, we see the footprints of the buildings of this block. One building is indicated by on logical unit surrounded in black.

These structuring inconsistencies complicates the detection of thematic changes from the real world between vintages. One possibility to overcome these structuring issues is to update all the vintages with a shared structuring criteria. This may for instance be done with an external reference source such as the cadastral plan. In our case, this was not an option since the cadastral plan is currently not available for each vintage (only the 2015 vintage is available). Therefore, we chose to structure the vintages according to a geometric criteria: two buildings are considered independent if they are non connected. This has been implemented in the *Split Building* action of *Step 1: Improving data quality* of the process presented in figure 5.1. *Split Building* is currently not applied on the 2015 vintage for technical reasons and to avoid losing its structure which is based on the cadastral plan. However, it harmonizes the 2009 and the 2012 vintages and reduces the differences with the 2015 vintages.

Finally, these quality issues may also be composed (e.g. geometry inaccuracy and structuring inconsistency, etc.) and do not only concern a few isolated cases but most of the buildings. In addition to these issues, one has to deal with formats evolution between vintages (e.g. different versions of CityGML in 2009 and in 2015).

5.1.2 Step 2: Detecting changes

The second step of our process presented in figure 5.1 consists in detecting geometric and thematic changes between vintages of the city. Given two vintages, we compare their city objects to detect unchanged ones, modified ones, creation or deletion, etc. These changes constitute *transactions* (presented in chapter 3) and they can be of five types stemming from the *TransactionValue* enumeration proposed and justified in chapter 3: *creation*, *demolition*, *modification*, *union* and *division*.

We identified two main methods for detecting changes between 3D city models in the CityGML format. Redweik and Becker [RB15] propose a method based on X-Diff [Wan+03] (allowing to detect changes in XML documents represented by unordered trees) and of a geometric comparison of the city objects. However, this method has not been evaluated on data acquired from the real world nor on large scale datasets and the implementation has not been made openly available to the best of our knowledge. Pédrinis et al. [Pé+15] propose a method to identify changes between two 3D city models by comparing its city objects based on geometric criteria. This comparison then allows to identify the following changes: unchanged geometry, modified geometry, constructed object, destructed object. This method completely leaves out the thematic aspect of the city objects and considers a set of geometric objects (two objects being considered independent if they are non connected) that are compared in two steps. First, the footprints of objects are compared to match those that have a non-zero intersection (and therefore that may be related) and to detect created and destructed objects. Then, the 3D geometry of the objects with footprints having a non-zero intersection are compared using the Hausdorff distance to determine if they are in the same state or if they have been modified. This proposition has been tested and evaluated on the 2009 and 2012 vintages of the city of Lyon and an implementation has been made available online by the authors. However, they leave out the thematic aspect of the city objects and the output of this process is one shapefile file per type of change (unchanged geometry, modified geometry, created objects and deleted objects).

Based on this analysis of existing methods, we chose to use the proposition of Pédrinis et al. [Pé+15] as a basis to detect geometric and thematic changes between

vintages. We updated this process in several ways. First, we introduced the *union* and *division* transactions types that were missing in this method with respect to the *TransactionValue* enumeration. Secondly, we introduced *the thematic structuring of city objects*: the base object used for the comparison is a city object (as defined thematically in the CityGML) and not a geometrical object (as initially done by Pédrinis et al. [Pé+15]). Therefore, we are able to detect city objects that are in the same state in two vintages but that have a different identifier. Thirdly, we updated the output (which was originally a set of shapefiles) to generate a graph where nodes are represent buildings (through their identifier) and edges express changes between these buildings. This graph is stored in JSON, following the GraphML conventions³. Finally, this process was initially integrated to a standalone tool (3DUSE). It has been made independent from the rest of the code and transformed into a command-line tool. This is implemented in the *Change Detection* action of *Step 2: Detecting changes* of the process presented in figure 5.1. In our case, we apply this action two times, respectively for the 2009 and 2012 vintages and for the 2012 and 2015 vintages, resulting in the production of two “*graphML inter-vintages changes*”.

5.1.3 Step 3: Aggregating into a time-evolving 3D city model

The last step of the process consists in using the corrected vintages from *Step 1* and the graphs from *Step 2* to create a time-evolving 3D city model in 3D Tiles with the temporal extension.

The “*graphML inter-vintages changes*” files are then loaded by the “*GraphML Reader*”. Then, the action named “*Graph Simplification*” is in charge of aggregating the two graphs and to simplify the resulting graph. The simplification consists in removing edges and nodes based on the following rule: If a city object (i.e. a node) is in the same state in two vintages V_1 and V_2 , keep the most recent city object (i.e. the one from V_2) and define its period of existence to $[V_1; V_2]$. This choice is based on the assumption that most recent vintages are of better quality (e.g. in terms of geometry precision and of structuring). In addition, one may argue that the city objects are not exactly the same in two vintages (in the real world, objects change at every moment, even in the smallest of ways). However, the current geometric precision of 3D city models do not allow to see these differences and the final purpose of this process is to create a dataset for interactive visualization (and therefore there is a need

³GraphML is a standard format for describing graphs, based on XML. Some propositions have already been made to write JSON files following the conventions of GraphML: <https://github.com/gregors/graphml2json> and <https://github.com/uskudnik/GraphGL/blob/master/examples/graphml-to-json.py>. We also chose this option to simplify the results

to optimize the dataset size). Once this step has been realized, the resulting city objects are loaded from the “*splitted vintages*” database by the “*3DCityDB Reader*” and handed to the “*Temporal Tiler*” along with the aggregated and simplified graph.

The “*Temporal Tiler*” is in charge of indexing the city objects. As explained in chapter 3, we currently implemented a kd-tree. A future enhancement would be to implement a spatio-temporal index (e.g. HR-tree [YP01]) which may result in better visualization performances. Finally, the “*3D Tiles Temporal Writer*” is in charge of writing the final dataset by following the 3D Tiles specification and the *3DTiles_temporal* extension⁴ presented in chapter 3.

This process can be installed and run by following this procedure : <https://archive.softwareheritage.org/swh:1:dir:3aa1541cdf3f05bb1a1409f7afb314ebc19ee2cd;origin=https://github.com/VCityTeam/UD-Reproducibility/>

5.2 Towards a modular architecture

At the beginning of this thesis, the existing system in our team was a standalone tool (3DUSE) containing several computation processes for geospatial data and a GUI for visualizing geospatial data (e.g. 3D city models in the CityGML format, shapefiles, etc.). Computation processes of 3DUSE include sunlight analyses [Jai+17] (finalized at the beginning of my thesis and conceived during my internship) and the process proposed by Pédrinis et al. [Pé+15] to detect changes between 3D city models (which served as a basis for the process of section 5.1.2) for instance. This tool was designed with a 2-tier architecture and is written in C++. In addition to 3DUSE, there was also a first web prototype based on a 4-tier architecture abandoned since.

During this thesis, we designed and implemented UD-SV⁵ (Urban Data Services and Visualization), which is a set of web based and open source components developed for research and industry in the geospatial field. UD-SV is based on a 4-tier architecture and is composed of components developed in our team and of others external to the team (including some of which we contribute to). The conception part has mainly been realized with my thesis advisors and with one engineer. The implementation part also involved interns. The 4-tier software architecture of UD-SV is presented in figure 5.4.

⁴<https://doi.org/10.5281/zenodo.3596881>

⁵<https://archive.softwareheritage.org/swh:1:rev:ba6573d19a83fc75bf8fd546f43c31696f65c1a7;origin=https://github.com/VCityTeam/UD-SV/>

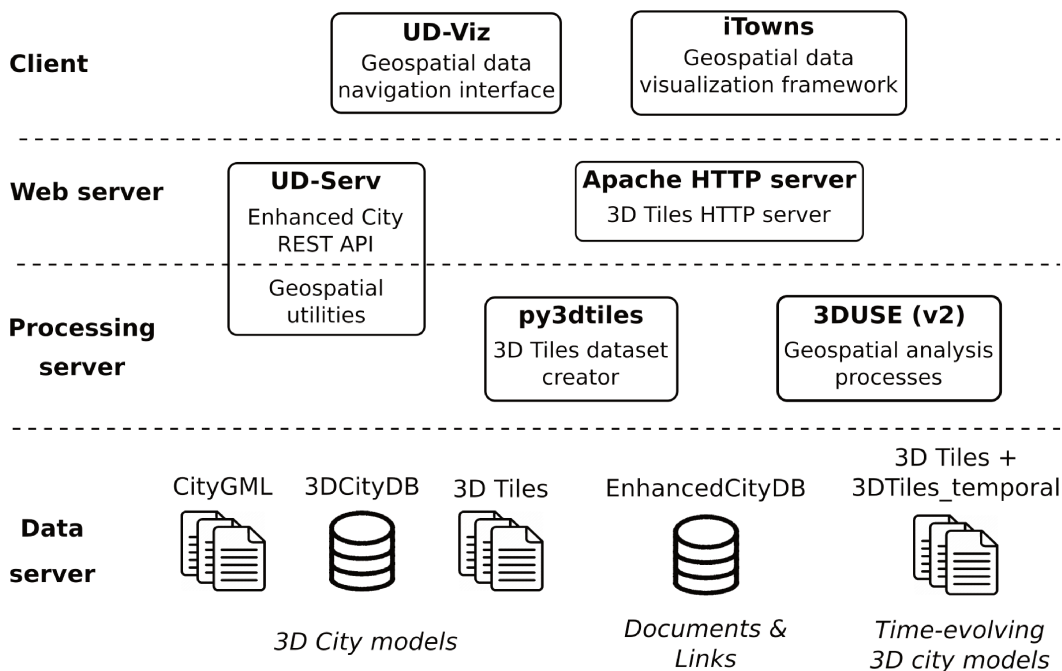


Figure 5.4.: Current 4-tier architecture of UD-SV (Urban Data Services and Visualization).

The data server layer The *data server layer* contains 3D city models represented in three different ways: as files in the CityGML format and in the 3D Tiles format and in a *3DCityDB* database. These representations serve various purposes. Some processes of UD-SV (those in 3DUSE) use CityGML files as inputs for historical reasons, while more recent processes (e.g. from *py3DTiles*) use a *3DCityDB* database. The 3D Tiles format is used for visualization in UD-Viz. In the future, it is planned that all processes will use databases instead of CityGML files in order to avoid parsing and to allow more efficient and complex queries. The *data server layer* is also composed of time-evolving 3D city models stored as 3D Tiles with the *3DTiles_temporal* extension, created with the process presented in section 5.1. Finally, another database *EnhancedCityDB* contains multimedia documents and links between multimedia documents and city objects.

The processing server layer The *processing server layer* contains an updated version of 3DUSE (v2)⁶, *py3DTiles*⁷ and one part of *UD-Serv*⁸ which is situated between the *processing server* and the *web service* layers. 3DUSE has been updated to a

⁶<https://archive.softwareheritage.org/swh:1:rev:0d643ee09460a7e3f594d5530eb0f0926286c6ab;origin=https://github.com/VCityTeam/3DUSE/>

⁷<https://archive.softwareheritage.org/swh:1:rev:bf28341f32998ddd96387da90dcfb63fa6133ce6;origin=https://github.com/Oslandia/py3dtiles/>

⁸<https://archive.softwareheritage.org/swh:1:rev:c89553bf9098246f59ec68df2b12501f698aff77;origin=https://github.com/VCityTeam/UD-Serv/>

new version (v2) where the GUI and the visualization parts are being deprecated and the computation processes are progressively being converted to independent command line tools for their integration with the other software components of *UD-SV*. This has been done for the *SplitBuilding* and *ChangeDetection* processes for instance (described in section 5.1). On the back-end side, we chose to implement our propositions related to 3D Tiles (e.g. *3DTiles_temporal* extension) into *Py3DTiles* (presented in section 3.3.1) which is developed and maintained by Oslandia⁹ (company working specialized on geospatial information). This choice stems from our desire to contribute to the geospatial community with open source developments. Finally, some utilities of *UD-Serv* are processes such as *CityGML2Stripper* which strips a CityGML 2.0 file from its appearance and generic attributes and serializes the result back into a new CityGML file.

The web server layer The *web server layer* contains the web service part of *UD-Serv* and an *Apache HTTP server* exposing 3D Tiles files (with and without the *3DTILES_temporal* extension). *UD-Serv* contains a REST API for Documents and Links (*API_Enhanced_City*, presented in section 4.3.1). *API_Enhanced_City* also holds the schema of *EnhancedCityDB* (data server layer) and allows to realize *Create*, *Read*, *Update*, *Delete* (CRUD) operations on this database. *UD-Serv* is programmed in python. In this thesis, we contributed to the conception and to the implementation of *UD-Serv* in collaboration with interns. In the future, *UD-Serv* may be separated in several individual software components to separate the processing utilities from the web service part.

The client layer The end-user application located on the *client layer* is *UD-Viz*¹⁰. It is written in JavaScript and based on several libraries, the main one being *iTowns*¹¹. *UD-Viz* manages the interface, multimedia documents and links, users (possibility to have an account, to realize CRUD operations on documents and links and to leave comments on multimedia documents) plus some useful modules such as address search. In this thesis, we contributed to its design and implementation (for instance with the contributions of chapters 3 and 4). *UD-Viz* mainly relies on *iTowns* for accessing and visualizing 2D and 3D geospatial information based on standards formats and protocols (e.g. 3D Tiles, WMS, WMTS, etc.). *iTowns* is based on WebGL

⁹<https://oslandia.com/en/>

¹⁰<https://archive.softwareheritage.org/swh:1:rev:b5a523825862a3f2dd440c2922485cdd30009834;origin=https://github.com/VCityTeam/UD-Viz/>

¹¹<https://archive.softwareheritage.org/swh:1:rev:e996369f1da742b8ca923f4c64d656f8d1a537db;origin=https://github.com/iTowns/itowns>

and ThreeJS and is mainly developed and maintained by the IGN¹² (historically also by Oslandia). The choice to base *UD-Viz* on *iTowns* also stems from our desire to contribute to the geospatial community with open source developments. In this way, our propositions have been implemented in *iTowns* as much as possible: a general criteria was to implement standards in *iTowns* and research propositions or prototypes in *UD-Viz* (and then to move them to *iTowns* if they are consolidated or standardized). For instance, we contributed to refactoring the management of 3D Tiles and implemented the *3DTiles_batch_table_hierarchy* extension. We also implemented a feature allowing to plug 3D Tiles extensions to *iTowns* from other software components¹³. This mechanism allowed to implement the *3DTiles_temporal* extension into *UD-Viz* and to plug it from *UD-Viz* into *iTowns* and it may be used for other 3D Tiles extensions in the future. Another choice could have been Cesium¹⁴ which is currently the most used JavaScript library for accessing and visualizing 3D geospatial information on the web. However, *iTowns* is more flexible on its roadmap than *Cesium* and the organization behind this project (the IGN) is more opened and responsive to our needs and propositions. Nevertheless, most of our contributions being based on well established standards, we are not completely tied with *iTowns* and switching to other libraries should be facilitated.

5.3 Reuse and reproducibility

One important aspect of this thesis is that we have done our best to propose reproducible, reusable and interoperable implementations. During this thesis and in collaboration with our team, we have conceived and applied a method to achieve these goals. The **interoperability** has been mainly achieved by using and extending **standards** when it was possible.

Regarding **reusability**, a best effort has been made to **contribute to existing software components** (e.g. *iTowns* and *py3dtiles*) and used for research and industry. In addition, all the software produced in the context of this thesis is **open source** (under the LGPL license). Moreover, we have done our to provide **documentation** describing software conception and developments¹⁵. This documentation is structured in *Needs*, *Issues* and *Design Notes*. *Needs* give information about the use case

¹²<http://www.ign.fr/>

¹³This proposition is currently on specific versions of *iTowns* and *UD-Viz* and in the process of validation by the *iTowns* team and of integration. However, it was discussed in advance with the *iTowns* development team.

¹⁴<https://cesium.com/cesiumjs/>

¹⁵<https://archive.softwareheritage.org/swh:1:dir:1cbd9ae93213fa9028cab3a1a5a935466b52fbe9;origin=https://github.com/VCityTeam/UD-SV/>

(user story), the impact of the development, the maturity and the evaluation of the development cost. *Issues* allow to organize the *Needs* in time and to provide milestones. *Design Notes* hold the technical choices related to the implementation resolving a *Need*. This methodology is based on AGILE software development methodology¹⁶, currently used a lot in computer science companies in order to work with short cycle of development. In addition, architecture documentation¹⁷ and tutorials¹⁸ have been produced. All this documentation has been made openly available. One current limitation is that this documentation lacks structure and maintenance which is costly in time. However, it eases collaboration with other researchers, engineers and interns (especially in a context with a lot of turnover where employment contracts are generally for short periods of time). However, we believe that producing such documentation can be a step forward in making research software development reusable.

Finally, we have paid particular attention to the **reproducibility** of the experiments and of the demonstrations realized in this thesis. First, we provide **permalinks to the specific versions of the code** allowing to reproduce the experiments by using the Software Heritage archive¹⁹. Secondly, we provide **permalinks to the data used and produced** in this thesis by using Zenodo²⁰. This guarantees durability of the data and source code. Thirdly, we provide detailed **installation scripts and notes** based on shell and Docker²¹ to install and reproduce the results and the demonstrations presented in this manuscript. They are all located in *UD-Reproducibility*²². In this way, one only needs to clone the *UD-Reproducibility* repository locally and to follow the installation notes to reproduce all our experiences. The process presented in section 5.1 has for instance been made available using this methodology.

¹⁶https://en.wikipedia.org/wiki/Agile_software_development

¹⁷<https://archive.softwareheritage.org/swh:1:rev:ba6573d19a83fc75bf8fd546f43c31696f65c1a7;origin=https://github.com/VCityTeam/UD-SV/>

¹⁸<https://archive.softwareheritage.org/swh:1:dir:6ee4fe233a4580db5f8e82434f376747e24c145a;origin=https://github.com/VCityTeam/UD-Viz/>

¹⁹<https://www.softwareheritage.org/>

²⁰<https://zenodo.org/>

²¹Docker (<https://www.docker.com/>) gives the possibility to define containers composed of an OS and specific packages that are needed for installing and running a given application. In this way, processes or services can be ran on any computer having docker installed.

²²<https://archive.softwareheritage.org/swh:1:rev:96c102a30b2278c5f863f0bc1a5d66122d7d622d;origin=https://github.com/VCityTeam/UD-Reproducibility/>

Multidisciplinary confrontation and contributions

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In this chapter, we present and discuss the multidisciplinary collaborations that took place during this thesis. We start by presenting a research contribution that is the result of a multidisciplinary collaboration: **DHAL** (Digital urban Heritage tools AnaLysis): a methodology to describe, analyze and compare digital urban heritage tools (section 6.1). This contribution involves me, Manon Istasse (post-doctoral fellow in sociology and anthropology), Sylvie Servigne and Gilles Gesquière (researchers in computer science), Michel Rautenberg (researcher in sociology) and Isabelle Lefort (researcher in geography). It stems from the wide variety of digital urban heritage tools that were identified and from the need to compare and analyze them. It has been published in the journal *Digital Applications in Archaeology and Cultural Heritage* [Jai+20b]. First reflections on this subject have also been proposed in [IJ17].

In section 6.2, we first propose a **discussion** highlighting **DHAL** advantages and possible future areas for improvement (section 6.2.1). Then, we **discuss the multidisciplinary collaborations** that took place in this thesis (section 6.2.2). This discussion is structured around three questions:

1. How a multidisciplinary context can enhance a thesis in computer science ?
2. To what extent this thesis benefits researchers of other disciplines and urban heritage experts ?
3. What difficulties and limitations arise from this multidisciplinary work and how could we overcome them ?

6.1 A multidisciplinary contribution: DHAL (Digital urban Heritage tools AnaLysis)

6.1.1 Context

Digital urban heritage tools allow to share existing knowledge with of apps or websites that are accessible to everyone or to a specific audience of specialists. In this way, they allow for understanding and perceiving the city, and its evolution over time. In some cases, participatory functionalities invite professionals and non-professionals to display what urban heritage is for them, participating in creating new knowledge. These tools take various forms. Some are databases (e.g. Australian

Heritage Database¹), while others offer types of interaction with data such as virtual tours (e.g. Avignon 3D [Ber+15]), and some include participatory functionalities (e.g. Transcribe Bentham [CW12], Monuments to the Dead in France and Belgium²). In this study, we focus on digital urban heritage tools that combine at least two of the three following aspects: **digital representation of the city** (e.g. maps, 3D models, etc.), **multimedia data** (text, audio stories, images, videos, etc.) documenting the city and its heritage, and **participatory functionalities** (comments, forums, submission of multimedia data, etc.). These aspects are indeed present in many digital urban heritage tools and are of particular interest in the Fab-Pat project.

Given this wide diversity, constructive critical analyses have to be conducted in order to describe and compare existing tools, to suggest areas for improvement of the functionalities they already offer, or to create new ones. Then, how should we describe, compare and analyse digital urban heritage tools in a qualitative frame? Our aim is to propose a scientific methodology that is:

- **systematic**, based on a structured group of terms allowing for a comparison that is as objective as possible;
- **qualitative**, in order to highlight the advantages, disadvantages and tracks for improvement of the tools;
- **multidisciplinary** and therefore constructed with multiple point of views, for proposing thorough analyses of these tools that involve several disciplines, for instance computer sciences and social sciences.

Several methodologies allowing for the analysis and comparison of digital tools have been proposed in recent years. Alatalo et al. [Ala+17] compare 3D web applications for participatory urban planning. Their analysis is based on elements related to technological performance (rendering performance, bandwidth needs, etc.) but also on qualitative elements based on the user experience (ergonomics, response time, etc.). In the U_CODE research project [Mü+17], they propose a searchable database to analyse thirty participatory urban planning projects conducted by local authorities. Farkas [Far17] focuses on web-mapping open-source software libraries for creating GIS web clients. He proposes a method of comparing and analysing these software libraries using metrics. Noordegraaf et al. [Noo+14] compare and evaluate crowdsourcing platforms developed by heritage institutions. Ginzarly et al. [Gin+19] analyse photos on Flickr to identify the way in which users (residents and tourists) perceive heritage at the city scale.

¹<http://www.environment.gov.au/cgi-bin/ahdb/search.pl>

²<https://monumentsmorts.univ-lille.fr/>

These methods have the advantage of offering relevant approaches, criteria and indicators. However, they are focused on types of tools that are more specific than those we want to analyse: participatory urban planning [Ala+17; Mü+17], web-mapping [Far17], crowdsourcing [Car+13; Noo+14], digital tools for citizen heritage [Lew+16], 3D reconstitution [Mü+16] and urban landscapes [Gin+19]. Moreover, these methods often stem from the questioning of a single discipline, whereas, following the recommendations of [Mü+16], a multidisciplinary approach is needed in order to offer a more comprehensive analysis. Finally, our goal is to propose a qualitative analysis, whereas most of these methods have the goal of rating tools in order to classify them or to create typologies to compare them.

Several typologies have been proposed for analysing and classifying participatory digital tools. They reveal that certain indicators are interdependent, such as the choice of tasks and the type of moderation [Lew+16]. They also offer a categorization according to specific entries. For example, the typology of participatory projects by cultural institutions developed by Oomen and Aroyo [OA11] contains four categories based on the tasks proposed to contributors (correcting, transcribing and contextualizing; completing, collecting and categorizing; crowdfunding; and co-curation). Taking the specific case of crowdsourcing, Ridge [Rid13] deepens these tasks and evaluate them in order to propose a more efficient citizen participation leading to data of better quality. The typology of [Lew+16] is composed of three categories (curated sites, content-hosting site and social networks) based on the contributors' involvement in the functioning of the tool. Wiggins and Crowston [WC10; WC14] are the only ones who propose a very complete typology of citizen science projects (not only focused on digital projects). However, the typologies are relative to a specific type of tools that are unconnected to digital heritage.

This examination of existing methods shows that each of them can contribute to the methodology that we want to establish. However, none of them is adequate by itself for attaining our objective of systematic, qualitative, and multidisciplinary analysis of digital urban heritage tools. In order to meet this need, we present a new methodology in the following sections: DHAL (Digital urban Heritage tools Analysis). We start by presenting the multidisciplinary process of construction of the methodology DHAL (section 6.1.2) before discussing the methodology itself (section 6.1.3). We finish with a short example of usage of DHAL (section 6.1.4).

6.1.2 Multidisciplinary co-construction

DHAL is made up of a collection of indicators³ allowing for the detailed description of tools combining digital representation of the city, multimedia data and participatory functionalities (figure 6.1). We have grouped these indicators into categories⁴ and sub-categories⁵ that we present in the following sub-section (table 6.1).

The construction of the indicators and their grouping stems from an iterative process depicted in figure 6.1. Four stages compose this process: (i) Indicators formalization, (ii) Tests on tools, (iii) Comparison with standards and typologies, and (iv) Comparison with field work. In order to refine the categories and indicators and to make this integrated approach more consistent and as complete as possible, we have iterated several times on these stages.

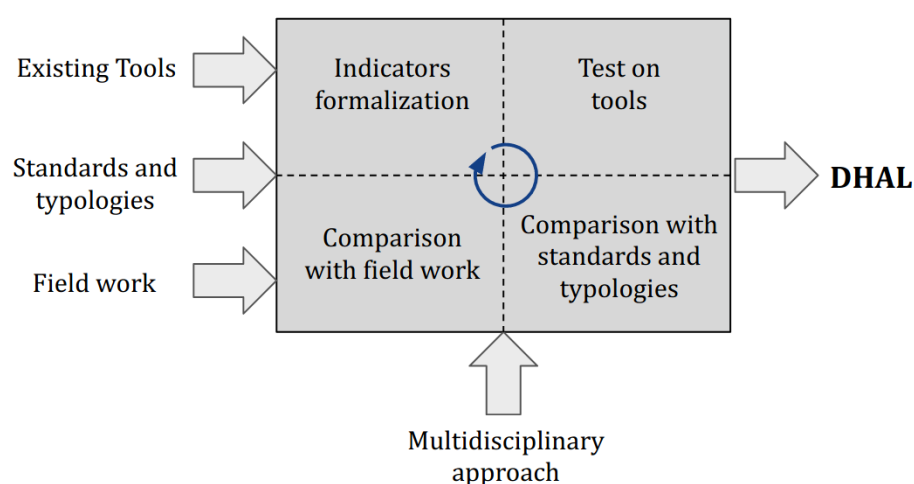


Figure 6.1.: DHAL construction process.

DHAL's construction in stages joins several sources. Firstly, it is based on the description and analysis of existing tools. Because of their diversity, they indeed implement many different methods and functionalities. Analyzing them hence has a heuristic function for establishing indicators (e.g., *richness of content* presented in detail in section 6.1.4) in the objective of proposing a systematic analysis methodology. We selected and analyzed fifty-four tools (presented in appendix C) that matched the three aspects of interest (digital representation of the city, multimedia data, and participatory functionalities). In addition to have a heuristic function for establishing indicators, this step brought us to generalize and categorize the indicators.

³In italic in the following.

⁴In bold in the following.

⁵Underlined in the following.

The indicators and categories that emerged with the analysis of existing tools have been seen in the context of existing standards and typologies. A large number of methods indeed rely on description norms and standards such as CIDOC-CRM [Doe03; Ara+18; Mes+18] and Dublin Core [Wei97; Kak+07; Sam+16]. In order to make the analysis of tools easier and to improve interoperability with tools and other analysis methodologies, we made the choice of relying on standards and typologies when possible. Therefore, some of DHAL's indicators names have been harmonized with CIDOC-CRM and Dublin Core, while other directly stem from these standards. In both cases, they are indicated with the CIDOC and DC mentions in figure 6.2 (for CIDOC-CRM and Dublin Core respectively). For instance, we replaced “temporal dimension of the urban data” with *time-span*⁶ from CIDOC-CRM and “proposed media” with *relation*⁷ from Dublin Core. Typologies of citizen science tools allowed us to add indicators such as contributors' *interests and motivations*, the timing of participation (*when*), and certain **objectives** of the tools.

We also carried out a field work (interviews and workshops) among people and organizations involved in cultural heritage (public institutions, local cultural heritage associations and citizens) in Lyon, France. This field work lead to the addition of indicators relating to **accessibility and visibility** and to the ways of **contributing content**. Moreover, as the methodology was constructed in an academic setting, it seemed essential to us to focus on the **thoughts on the tool**, whether internal or external, particularly in order to improve it.

Finally, the multidisciplinary approach has led to (i) broaden the scope of indicators and (ii) specify the indicators. Some indicators come from the field of social science, especially those that imply a qualitative investigation of what users do with the tool (e.g. required *skills, modes of resistance*⁸). Others, such as those related to the content and its mode of representation, come from computer sciences. In a similar manner, some categories such as **objectives** and **thoughts on the tool** are more related to research issues in the social sciences, while others, such as **content** and **navigation in content** are more related to computer sciences. The confrontation of the disciplines has led to refine and harmonize the indicators both at the vocabulary level (discussions on the distinction between information and content, multimedia and urban data, system and tool, etc.) and at the level of their usefulness (explaining the relevance of certain indicators that were not immediately clear for researchers

⁶See definition of time-span page 26 of the current official version (6.2.3) of CIDOC-CRM : http://www.cidoc-crm.org/sites/default/files/2018-05-16%23CIDOC%20CRM_v6.2.3_esIP%28XDP%29%28XM%29.pdf

⁷<http://dublincore.org/specifications/dublin-core/dcmi-terms/2012-06-14/?v=elements#relation>

⁸Resistance can take the form of not using the tool, misusing it, or not respecting standards and policy charters.

in another discipline). Therefore, in addition to being a methodology, DHAL has a heuristic function in the implementation of scientific plurality and illustrates the need to work conjointly across disciplines.

6.1.3 Presentation of the methodology

DHAL is based on a set of indicators and structured in categories. They are presented in figure 6.2 as a mind map. The indicators are situated on the leaves of the mind map and the categories and sub categories constitute branches. This representation facilitates the understanding of DHAL and can be used for analyzing digital urban heritage tools. More specifically, a digital urban heritage tool can be placed at the center of the mind map and analyzed according to the branches (i.e. the categories and sub-categories) and to the leaves (i.e. indicators) of the mind map. Indicators stemming from CIDOC-CRM and Dublin Core are indicated with the mentions (CIDOC) and (DC) respectively.

For readability reasons, we do not describe each indicator individually here. However, they are presented through an analysis of twelve digital urban heritage tool in section 6.1.4. In addition, we present and describe the categories in table 6.1. These categories emerged while defining the indicators. They allow better understanding of DHAL and facilitates its use. Some categories (and therefore all their indicators) can indeed be dropped if they correspond to an aspect not managed by the analyzed tool. For instance, in the case of a non-participatory tool, it is possible to drop the **contributing content** category (and therefore all its indicators). Furthermore, these categories reflect the types of tools we chose to analyze (combining at least two of the three following aspects: digital representation of the city, multimedia data and participatory functionalities) and the setting in which DHAL has been constructed (e.g. the **thoughts on the tool** category reflects the academic setting).

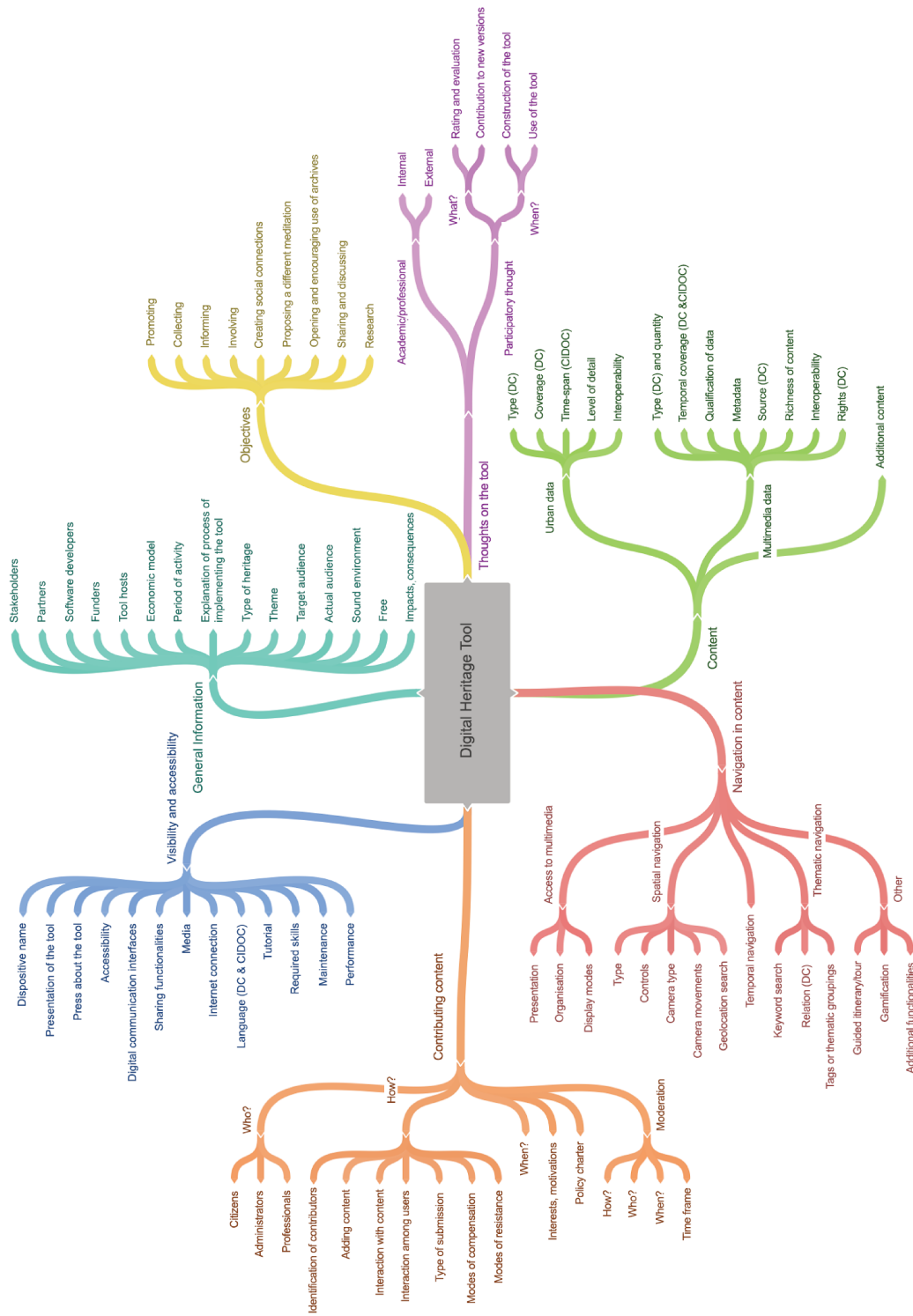


Figure 6.2.: Representation of DHAL's indicators (leaves) and categories (branches) as a mind map. Indicators defined in Dublin Core or CIDOC-CRM are indicated with the mentions DC and CIDOC respectively.

Category of indicators	Description
General Information	Describing the people involved, the activity period of the tool, the economic model, the type of heritage represented, the theme (urban, architectural, industrial, etc.), the target and actual audience or the impacts and consequences related to the tool.
Objectives	Describing the tool's objectives (promoting, collecting, informing, etc.)
Thoughts on the tool	Describing thoughts on the tool, whether they are academic or professional (internal or external) or participatory (how and at what stages of the project).
Content	Describing urban and multimedia data and any additional content, in terms of type, quantity, spatial and time-span, etc.
Navigation in content	Describing the modes of access to multimedia data (presented as a list or as hotspots, organization, display modes) and navigation in content (spatial, temporal, or thematic). This category also allows for describing possible additional functionalities, such as gamification.
Contributing content	Describing who participates, how (methods implemented for allowing and/or encouraging participation, appropriation of modes of participation by contributors, etc.), when (limited or unlimited duration of participation), and why (interests and motivations for participation). Other indicators address the methods of moderation and indicate the presence of a policy charter for participation.
Visibility and accessibility	Describing the methods established to make the tool visible and accessible. The name of the tool, the indicators relating to media and the press, and the sharing functionalities (the participants sharing their actions) are mainly related to the tool's visibility while the other indicators are related to its accessibility.

Table 6.1.: Indicators categories and descriptions.

6.1.4 Example of usage on twelve digital urban heritage tools

In this section, we illustrate the usage of DHAL with an excerpt of an analysis conducted on twelve digital urban heritage tools. They are numbered (the first twelve ones) and indicated in bold in Appendix C. This choice was guided by needs and questions of the Fab-Pat project as well as by the aim to reflect the variety of the fifty-four tools of table C.1 in terms of functionalities, size and success. However, analyses arising from this example of usage do not pretend to any exhaustiveness nor to reflect the diversity of digital urban heritage tools in general.

This analysis has been realized in two steps. The first step consists in analyzing each project independently according to DHAL's indicators by filling a table. For readability concerns, we only present an extract of this table (regarding the **content**) for the tools *Past virtual tour of the Château de Chenonceau* and *Inventory of Monuments to the Dead* (table 6.2). The second step, consists in comparing the each tools according to this table to discover trends and interesting potentials. We present an extract of this comparative analysis in the following.

The **general information** category gives an overview of tools. The twelve tools are available for *free*. They have been *created* between 2003 and 2015. Except those downloaded on Smartphones, they all need an *Internet access* to be used. In terms of *types of heritage*, most tools present some element of official heritage and four present memorial or unofficial heritage. Out of these four tools, one (3⁹) is interested only in unofficial heritage and three (10,11,12) are interested in both official and unofficial heritage. It should be noted that the integration of participatory functionalities seems to go hand in hand with openness to less official heritage, either because the desire of the stakeholders is to bring this out, or because this is naturally what the contributors add. Within these types, tools generally present a main *theme*: urban and/or architectural heritage. We noticed an absence of rural heritage. Finally, the twelve tools involve various actors. There is a wide range of *stakeholders*: associations, local authorities, private digital companies, public organizations, universities and research committees. One has to notice that a partnership between a university and public organizations - as it is the case for the Fab-Pat project - is not at odd. These stakeholders may rely on a service provider to *develop their software* (1,2,4,5,7,9,10,11). Among the four tools involving a university or a research institution (3,4,8,11), two called upon a service provider for software development (4,11). This implies that no computer science laboratory was involved - contrary to the Fab-Pat project - and that only researchers in social sciences were involved (which is confirmed by the list of partners).

⁹we indicate which tools are concerned with their number from Appendix C.

	Past virtual tour of the Château de Chenonceau	Inventory of Monuments to the Dead
<u>Urban data</u>		
Type	3D (exterior of the castle) and 2D (720° pictures of the interior)	2D map (based on Google Maps), only used to localize the monuments
Coverage	Castle and outbuildings	France and Belgium
Time-span	Present	Present
Level of Detail	No precise details available. General 3D view of the castle and high definitions pictures	Provided by Google maps
Interoperability	No details available	Provided by Google maps
<u>Multimedia data</u>		
Type and Quantity	Approximately 40 pictures plus textual information	Pictures (more than 20.000), descriptive texts (main media), geolocation maps
Temporal coverage	Not applicable	Since 1870
Qualification of data	No details available	Can be specified by contributors when adding data. For instance, is it based on a scientific source or is it a rumour?
Metadata	None	Numerous. For instance, about a monument: location, description, inscription on the monument, material used to build the monument, comments on the style, price and funders, etc.
Source	Managers of the project	Anonymous contributions
Richness of content	Basic	Intermediary
Interoperability	No details available	No details available
Rights	Not applicable	Creative commons for pictures
Additional content	Brief information about rooms and places related to the castle on the welcome page	None

Table 6.2.: Extract of the comparison table of the tools Past virtual tour of the Château de Chenonceau and Inventory of Monuments to the Dead according to the **content** category of DHAL.

A second category of indicators relates to the **objectives** of tools. The number of tools per objective is presented in figure 6.3, where participatory tools are represented in light grey and non-participatory ones in black. Objectives indeed take an interesting turn when they are related to the participatory dimension. *Collecting* documents and information is clearly the purpose of participatory tools (3,6,11,12), but they are not limited to this, since they most often also have objectives of *sharing* (3,6,12), *creating social connections* (3,9,12), and *mobilizing* users (3,6,12). Non-participatory tools encourage a *different mediation* of heritage (1,2,4,5,7,8) and *opening and encouraging use of archives and heritage* (1,2,7,8). Out of the four tools with a research objective (3,4,8,11), two are participatory (3,11) and two are not (4,8). The latter group mainly aims to compare 3D reconstructions to scientific knowledge. Finally, it is interesting to note (and to identify using DHAL) that a planned objective may not be attained and that an objective that was not initially planned may emerge as the tool is used. For example, a tool that had the objective of *collecting* and *promoting* data can lead to the *creation of social connections* even though this was not one of its initial goals (for instance 11).

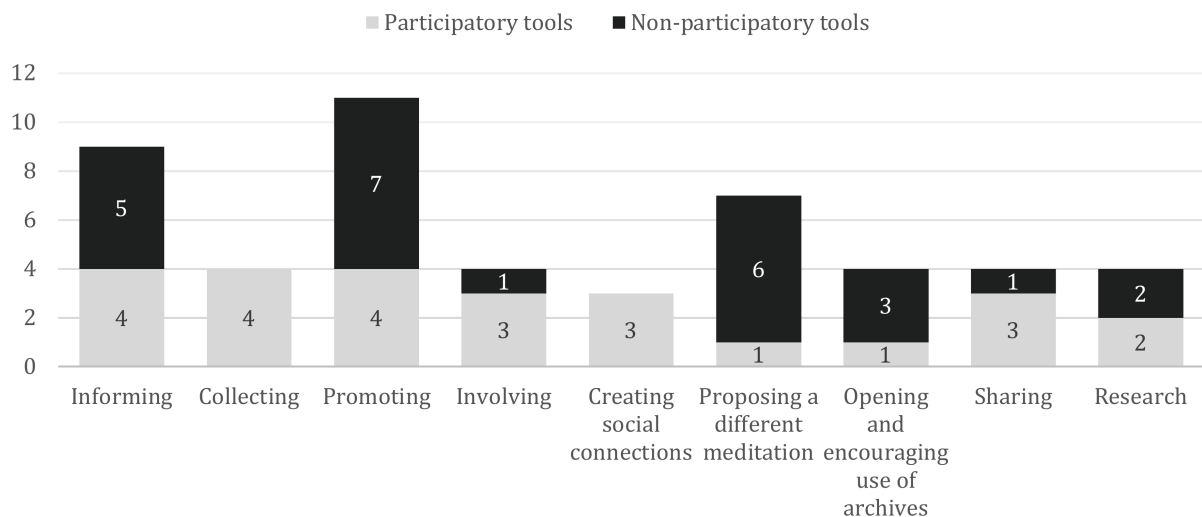


Figure 6.3.: Objectives of the tools. The participatory tools are represented in light grey and the non-participatory tools are represented in black.

The **content** of the tools in terms of urban data can be of different *types*: 2D map (3,5,6,7,8,9,10,11,12), panoramic pictures (1,2,4), or 3D models (2,3,8). It is also interesting to note that some tools offer multiple modes of representation of urban data (3D models and 2D maps, for example) that can serve different uses. For instance, a 3D model for the reconstruction of a monument and a 2D map to specify its geolocation on a larger map. Correlating the *type* and *coverage* indicators shows that the tools offering a 3D model (2,8) have relatively limited *coverage* (limited to

a monument) - while our prototype allows to manage digital 3D models of cities. This mode of representation is especially used for virtual tours of buildings that have been reconstructed in their prior condition. Finally, most tools limit the *time-span* of their digital urban model to a specific year.

Time coverage of multimedia data is however wider, as they are generally more accessible than 3D models for instance. Moreover, many tools (1,4,6,7,8,10,11) aim at collecting multimedia data related to the past. The *metadata* associated with multimedia data greatly vary. One tool (2) contain no metadata, seven (1,3,5,6,7,8,9) contain only three or four (name, date, description, creator), three (4,11,12) add more specific information (architectural movement, date of destruction, conflicts involved) and one (10) leaves the user free to add any metadata information. In the case of participatory tools, available *metadata* is generally linked to the chosen mode of participation. For instance, if the submission is open to every contribution, little metadata is generally required. Finally, tools can be qualified using the *richness of content* indicator, which is composed of three categories:

- Basic (2,6,9): the content includes text, current photos, and little metadata. Content is presented as photo slideshows and hotspots providing information on points of interest.
- Intermediary (1,3,4,5,7,11,12): in addition to the basic content, there are audio files, archival photos, maps, and a great deal of metadata.
- Advanced (8,10): in addition to the intermediary content, there can be videos, audio-guides with geolocation information, or comic strips. The modes of representation can allow for temporal comparison (comparison of photos of the same area at different dates for instance).

In the category **navigation in content**, access to multimedia mainly occurs through a *presentation* in the form of lists (1,3,4,5,6,8,10,11,12) or using geolocation on the tools' urban models (1,2,3,4,6,7,8,9,10,11). Three tools (4,6,7) offer *organization* by theme or era. Thematic navigation of multimedia (e.g. access to medias through semantic information or through common themes) is very frequently present in the twelve tools. Seven of them (3,5,6,9,10,11,12) offer *keyword search* in the title and associated metadata, only two (4,5) contain direct *relations* between multimedia, and six (3,4,6,7,9,10) offer *thematic grouping of multimedia* (e.g. medias related to themes such as architecture, history, etc.). One tool offers adding *tags* defined by users, allowing navigation through the multimedia. Temporal navigation in data is rarely possible or is limited to a few dates (1,4,8,12). Only three tools do not propose spatial navigation. Other propose *camera* rotations (1,2,4), guided or semi-guided

Contributing content: how		
Adding content	creating a file or a collection	4 (3, 10, 11, 12)
	adding multimedia documents	2 (3, 11)
Interaction with content	modifying	1 (12)
	commenting	3 (3, 9, 10)
	rating	1 (10)
	sharing	1 (9)
Interaction among users	comment tools	4 (3, 9, 10, 12)
	discussion page	1 (12)

Table 6.3.: Ways of contributing content.

moves (1,3,10) and free moves (6,7,9). Most tools allow a *geolocation search* by clicking on geolocated points of interest. Both spatial and temporal navigation may be improved by allowing continuous navigation in urban and multimedia data in space and in time for instance. Finally, four tools (5,8,9,10) offer *gamification* mechanisms. For three of them (5,8,10), this takes place as games (quizzes, etc.). The remaining one (9) propose mechanisms for participation compensation (change of status, etc.). These mechanisms are used in all participatory tools that have been successful in terms of number of contributors.

In terms of **contributing content**, seven tools are not participatory (1,2,4,5,6,7,8): only the *administrators* can add or modify content. In the five others (3,9,10,11,12), users can also contribute in various ways (table 6.3): *adding content*, *interaction with content*, or *interaction among users*.

Additions and interactions occurs as follow. First of all, the five participatory tools require the *identification* of the contributor by signing in (3,9,10,12) or providing an email address (11) when the contribution is made. The contributors only rarely benefit from compensation by a change in status (9). The form of contribution is most often guided - i.e. structured with required fields to fill out (title, description, localization, etc.) while others are optional (date of construction or modification, architect, etc.). In the case of four tools (3,10,11,12), contributors can get help from a *tutorial* that explains how to contribute, and they must observe a *policy charter* (9,10,12) that regulates, for example, discussion in the comments section. Three tools also have visible *moderation*. In the case of pre-moderation (11), any new content to be added must be validated by administrators before becoming public. It should be noted that the only tool that proposes only adding content, with

no possibility of interaction, is also the only one that has pre-moderation. With post-moderation (9,10), content that is not compliant may be removed after having been made public if it is flagged by a user.

Contributors participate only in the context of the use of the tools and not in its construction. However, they can take part in **thoughts on the tool**, either by giving it a *rating* (10), or by making *contributions to new versions* (9,11). In this way, in terms of participatory thinking, elements (particularly blog posts) lead us to believe that discussions took place regarding the use of the tool and that modifications were made following these discussions. *Professional or academic thoughts* concerns only three tools (3,8,11) whose development is accompanied by either scientific papers or a blog managed by academics reporting on the project's progress.

6.2 Discussion

6.2.1 Discussion on DHAL

In addition to DHAL's usefulness for the Fab-Pat project, several advantages emerged during its construction and usage. First, the variety of indicators originating from several sources and designed with multidisciplinary point of views allows for a systematic, qualitative and multidisciplinary analysis. The use of DHAL leads to an overall view of the tools that is more significant than using typologies and other methods presented in section 6.1.1. Secondly, as shown in section 6.1.4, relating indicators to each other brings out interesting analysis elements. Other relations between indicators may be considered. For instance, it may be possible to gather elements regarding a tool's success by comparing indicators such as *target audience* and *actual audience*, by focusing on *impacts and consequences* subsec(e.g. certification, prizes, number of downloads or views, etc.) and, in the case of participatory tools, by looking at the number of multimedia files contributed by users outside the circle of administrators. Finally, DHAL allows for a qualitative analysis of tools, which can help when studying them or when constructing new ones.

DHAL may also be used to conduct quantitative analyses of digital urban heritage tools. After having defined specific objectives, it may be possible to assign a weight to the indicators. For example, the need to find a fun participatory tool can lead to grant more weight to the indicators *gamification*, *mode of compensation*, and *interaction with content*. This use of DHAL may allow for rating tools in order to classify them, the highest-ranked being the one that meets the predefined needs the

best overall. To go a bit further, it may also be possible to make certain indicators (or categories) discriminating. An indicator (category) may be discriminating if a tool with a score that is zero or that is below a certain threshold for this indicator (category) therefore receives an overall score of zero so that it is placed at the bottom of the classification. For example, if one of the needs is the participatory aspect, then the category **contributing content** can become discriminating. The, if a system has a score of zero for this category, its overall score will be zero. This kind of quantitative analysis can be useful in particular for classifying tools in order to select the one that is most appropriate to specific needs.

A possible improvement concerns defining ranges for indicators' values. They are currently defined according to one's specific needs and on the basis of the characteristics of the tools analyzed. For example, *coverage of urban data* includes in our case: monument, area of a city, city, country, and world. However, this choice can be problematic in some cases. For example, how should we categorize a multi-scale tool representing both monuments and a city? In section 6.1.4, we choose to classify the tool in the category of the largest area it represents. This list could also be different for other types of tools, such as those related to rural areas which may have values such as municipal territory, natural countryside, etc. Therefore, providing predefined ranges could be an enhancement for the future.

If digital urban heritage tools could be further developed, so do DHAL. We proposed a version of DHAL with structured guidelines that any user of the methodology can adapt to his objectives. In that way, DHAL is a flexible methodology. However, some indicators may be refined such as *impacts and consequences* (number of downloads, certifications, prizes, user notes) by relying on the metrics proposed by Farkas [Far17]. We could also detail those related to *interaction among users*: while we have mentioned those that take place online, those that may take place offline or in another digital space are absent. This is also the case for *interaction with content*, which can consist in correcting, transcribing, localizing, describing, etc. We did not carry out this subdivision due to our objective of general description of the tools. However, indicators may be refined depending on the type of tools analysed and on specific analysis needs. In addition, the usage of DHAL showed that some indicators might be difficult to fill out. For instance, it is necessary to know well the tools analyzed in order to find information about *target audience*, *actual audience*, *modes of resistance*, and *motivations and interests of contributors*. One might indeed need to conduct a qualitative investigation of users of the tools to fill out these indicators. Finally, it may be interesting to propose a software implementing DHAL and offering comparison functionalities between digital urban heritage tools.

6.2.2 Discussion on multidisciplinary work

This discussion is not intended to give the recipe to conduct successful and seamlessly multidisciplinary work nor to discuss and analyze multidisciplinary work in general. However, it aims at providing feedback on this aspect based on the work that took place during this thesis, in the form of lessons learned and with some propositions that may facilitate this work in the future.

The research contribution presented in section 6.1 is a practical example of the benefits of the multidisciplinary collaborations that took place in this thesis. It might indeed have been limited to the computer science aspect or might not have been proposed at all otherwise. In addition, working together on a scientific paper (on the same object and not on different parts that are assembled in the paper afterwards) obliges to align different methodologies, to make compromises and to find a balance in order that everyone is happy with the resulting work. Furthermore, these multidisciplinary collaboration led to enhance the contributions of this thesis with real use cases, thoughts and questions related to practical usage. However, such collaborations are challenging due to the differences between disciplines in terms of vocabulary, methods, questioning and objectives. Such differences, which also arise when working with people from the same discipline, are intensified in a multidisciplinary context.

Misunderstandings in terms of vocabulary may stem from a lack of knowledge of the discipline. Words and expressions such as “data model” or “client-server architecture” are for instance generally not understood by non experts in computer science. In a similar way, concepts like “cultural heritage”, “participation”, “moderation” are not always fully grasped by non experts in cultural heritage or citizen participation. Beyond these inter-discipline technicalities, misunderstandings are generally due to the use of the same word but with different meanings. This highlights the need to define a shared glossary from the outset of a project, to stick to it and to enhance it during the project. In the context of this thesis, this work has been undertaken for the contribution presented in section 6.1. However, it has not been extended to all the multidisciplinary collaborations. Existing propositions may guide and feed glossaries of future multidisciplinary projects. In the geospatial community for instance, standardization organizations proposed guidelines to define cross-domain vocabularies [Int10] and have their own glossary (e.g. OGC¹⁰ and ISO [Int08]).

Questioning, methods and objectives also differ between disciplines. This is not fundamentally a bad thing. However, joint work asks for understanding of these

¹⁰<https://www.opengeospatial.org/ogc/glossary>

questioning and methods. In particular, it may be difficult to understand what constitutes a challenge in a different discipline and what methods may be involved to overcome it. Therefore, we believe that an immersion in the other discipline is needed to facilitate multidisciplinary collaborations. As a first step, reading scientific research papers allow to grasp some of the issues, contributions and methods of a discipline. In addition to that, an immersion in the practical world of other disciplines allows to go further in understanding of the scientific locks and of the methods involved to overcome them. This has been done in the context of this thesis with Manon Istasse (post-doctoral fellow in sociology and anthropology). It took place in the form of field work (interviews and discussion with urban heritage actors of the city of Lyon) for me. For Manon, it consisted on demystifying what's behind a digital tool: models, methods, algorithms, etc. This work however requires an effort of abstraction of the concepts and methods of your discipline and asks for opening to other methods and approaches, as in any good conversation. Another problem lies in the fact that one's needs and objectives are not always well expressed, while it is essential for fruitful collaborations. One possibility is to compel oneself to clearly write its needs and objectives and to review them with multidisciplinary partners. To this end, it may be possible to adapt some methods such as Agile software development¹¹ (mainly used for software development) to multidisciplinary research work. More specifically, it seems adequate to reuse some of their core concept (e.g. clearly write the needs, evaluate the time needed for realization, work with short cycles of production, etc.).

Other collaborations took place in this thesis and in particular with urban heritage experts. In addition to bringing an expert perspective to the discussions, they also acted as potential users and broadcasters of the prototype. In the context of the thesis, it has led to precisising the needs of being able to represent and interact with the evolution of cities as well as the possibility to integrate multimedia documents to digital cities representation for navigation. In addition, their knowledge of the cultural heritage actors allowed to initiate a collaboration with the “cultural heritage and general inventory” department of the *Auvergne-Rhône-Alpes* region (France). This partnership has led to the integration of some multimedia documents from their official database (that can be consulted online¹²) in our prototype. This integration is a first step allowing (*i*) to demonstrate the possible usability of the prototype resulting from the research proposed in this thesis and (*ii*) to propose prospective elements to this institution on how partnerships with research institutions and how more evolved digital tools may be beneficial for them.

¹¹https://en.wikipedia.org/wiki/Agile_software_development

¹²<https://patrimoine.auvergnerhonealpes.fr/>

In conclusion, multidisciplinary collaborations allowed to enhance this thesis in computer science by feeding the needs and possible usages. In addition, they led to a joint multidisciplinary scientific research contribution [Jai+20b] (section 6.1), which also benefits researchers of other disciplines. The contributions of this thesis led to a prototype that received an enthusiastic response from urban heritage experts and first collaborations have even been set up. Finally, we outlined several difficulties that may arise from multidisciplinary work and proposed proposed methods to overcome them.

Conclusion

Contents

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7.1 Contributions

In this thesis, we focused on the **integration of the temporal dimension and multimedia documents to 3D city models for web visualization and navigation**, with the aim of enriching 3D city models to help understanding the city and its evolution. We have broken down this problem into two research questions that we addressed with scientific and technical contributions in this thesis.

First, we addressed the **formalization of the temporal dimension of 3D city models for interactive web navigation and visualization**. Based on the observation that standard formats for large 3D geospatial datasets visualization on the web (3D Tiles and I3S) share concepts and lack conceptualization, we proposed **Gen3DGeo**: a generic conceptual model for delivering 3D geographic features for web visualization based on standard formats. We integrated a formalization of the temporal dimension that we proposed based on existing propositions to *Gen3DGeo*, resulting in **Gen4DCity**: a generic conceptual model for time-evolving 3D city models visualization on the web. *Gen4DCity* has been specified at the logical and specification level into the 3D Tiles standard. Based on the lack of logical model of 3D Tiles, we proposed **Logic3DGeo** which is a specification of *Gen3DGeo* in the 3D Tiles standard. We also proposed **Logic4DCity** which extends *Logic3DGeo* with the temporal extension (and which is therefore a specification of *Gen4DCity*). At the technical level, we proposed the **3DTiles_temporal** model, extending 3D Tiles to integrate the temporal dimension of cities. Therefore, in addition to integrating the temporal dimension to 3D city models for web visualization, we provided a conceptualization of existing standard formats. We also provided an open source implementation and evaluated these propositions with reproducible experiments, allowing to prove that it allows to achieve interactive visualization. These contributions constitute a step forward in the visualization and navigation of 3D cities evolution on the web, which may help cultural heritage experts and urban planners in their objectives. This work has been accepted for publication in the *International Journal of Geographical Information Science* [Jai+20a].

Secondly, we addressed the **integration of multimedia documents and 3D city models for visualization and navigation on the web**. We proposed **GenLinkable**: a generic conceptual model for features integration. We used this model for multimedia documents and time-evolving 3D city models integration at the conceptual level, resulting in the **Gen4DCity-Doc** model, enhancing *Gen4DCity*. This proposition allows to document geographic features and concepts describing their evolution in time. We provided an open source implementation and provided a demonstration

of the new possibilities brought by this proposition in terms of thematic navigation. This contribution has multiple applications such as helping to justify cities evolution or documenting cultural heritage. A scientific paper describing this contribution is currently in preparation for submission to the *ISPRS International Journal of Geo-Information*.

Addressing these research questions led us to tackle technical challenges. We provided an **automated and openly available pipeline** for the **creation of time-evolving 3D city models** which takes into account and corrects some of the quality problems identified in current 3D city models. We also provided a **4-tier architecture** for enhanced 3D city models web visualization and navigation based on new and existing open source software components (from research and industry). One difficulty lied in the current unstable context in terms of standards, tools and technologies for 3D geospatial information management and visualization on the web. Moreover, we did a best effort to propose contributions that are interoperable, reusable and reproducible. A paper presenting the architecture of this platform and the scientific contributions it encompasses is currently being written.

We also proposed a multidisciplinary research contribution realized in collaboration with researchers in social sciences and in geography: DHAL (Digital urban Heritage tools AnaLysis). This contribution can help to analyze existing digital urban heritage tools and to design new ones. It has been accepted for publication in *Digital Applications in Archaeology and Cultural Heritage* journal [Jai+20b]. Moreover, we discussed the multidisciplinary contributions that took place in this thesis, highlighted their limits and proposed method to overcome them, which could be used for future multidisciplinary work.

Finally, our contribution and our tool have been presented and made available to the partners of the Fab-Pat project. Beyond possible ergonomic improvements, it has been tested and found useful by urban heritage experts. In particular, the “cultural heritage and general inventory” department of the *Auvergne-Rhône-Alpes* region (France) asked for a demonstration of our tool integrating some of their multimedia documents for communication within their services and towards the outside.

7.2 Perspectives

Some perspectives of enhancement of our contributions from chapters 3 and 4 have already been presented in sections 3.4 and 4.4 respectively. We will not detail them

further here. However, we present other perspectives of evolution of our work in a more general way.

A first short term lead is to implement the link between multimedia documents and concepts representing cities evolution such as transactions (therefore integrating the implementations of our contributions from chapter 3 and 4). This would result in a web based information system for visualization and navigation in time-evolving and documented large scale 3D city models. These implementations have been designed in a modular way in order to ease their integration. A more long term goal would be to specify *GenLinkable* (see section 4.1) for other type of features than multimedia documents and 3D city models. One identified use case [CK19] is for smart cities related applications, that would benefit from integrating real-time sensor data (e.g. energy consumption of a building, room temperature, etc.) to 3D city models.

In addition to these perspectives, discussions with partners of the Fab-Pat project have led to the identification of other needs for cultural heritage sharing and shaping, that raise computer science research problems.

A first need that has been raised is to open our system for use by the general public. This may allow to gather resources and knowledge from citizens, cultural heritage enthusiasts, associations, etc., for instance in the form of multimedia documents. This would benefit institutions (e.g. cultural heritage department of cities) or researchers in the cultural heritage field to know more about how citizens experience cultural heritage and what defines cultural heritage for them. Moreover, it could facilitate their integration in cultural heritage shaping. First, this need raises questions regarding moderation, target audience, type of knowledge that may be gathered (e.g. multimedia documents? which ones? etc.), community animation, type of contribution (open? regulated?), etc. that may need to be resolved by experts in social sciences and cultural heritage. Our contribution from chapter 6 (the methodology DHAL and the proposed analysis of existing digital urban heritage tools) may help in this task. Then, it may also raise computer science questions. Evident first questions that would need to be resolved are regarding the amount of data that would be gathered: how to manage a big amount of multimedia documents in terms of storage, navigation and visualization? Then, other issues may be raised regarding quality of the data that is contributed. This is still an open question, especially for systems based on volunteered geospatial information [Sen+17].

In this thesis, we mainly focused on tangible cultural heritage (represented by city objects of 3D city models). However, cultural heritage also encompass intangible cultural heritage (e.g. oral traditions, performing arts, rituals). Further studies may be needed to integrate intangible cultural heritage with 3D city models and to

provide navigation and visualization possibilities since it is generally not represented by a physical artifact. The integration of intangible cultural heritage in our system would require to provide a model to describe it. One first simple possibility would be to identify intangible cultural heritage elements by their name and eventually a type (e.g. based on the ontology proposed in [Tan+09]). Then, our *GenLinkable* model would allow to create links between intangible cultural heritage elements and multimedia documents (describing them) or city objects (e.g. a ritual that refers to a specific building or park where it takes place, etc.). Furthermore, integrating intangible cultural heritage may also raise questions in terms of navigation and visualization possibilities since they are concepts and not physical quantifiable things.

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Appendix A: 3D Tiles and I3S conceptual models

In this appendix, we propose conceptual models of 3D Tiles (figure A.1) and of I3S (figure A.2). These models have been designed as a first step before proposing *Gen3DGeo* (figure 3.1).

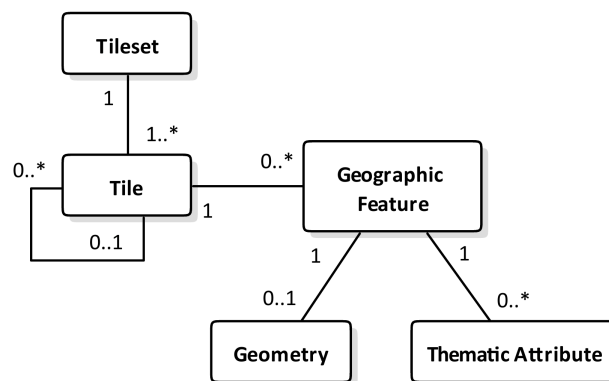


Figure A.1.: Proposed conceptual model of 3D Tiles.

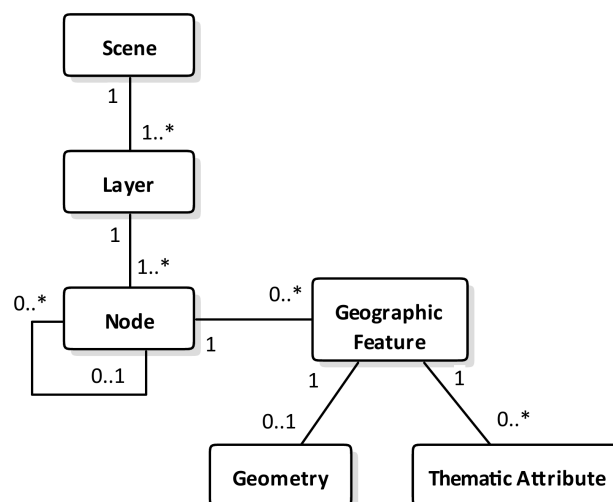


Figure A.2.: Proposed conceptual model of I3S.

Appendix B: Link and Multimedia Document physical model

In this appendix, we present the physical model of *DocCityObjectLink* allowing to link multimedia documents and 3D city objects [B.1](#).

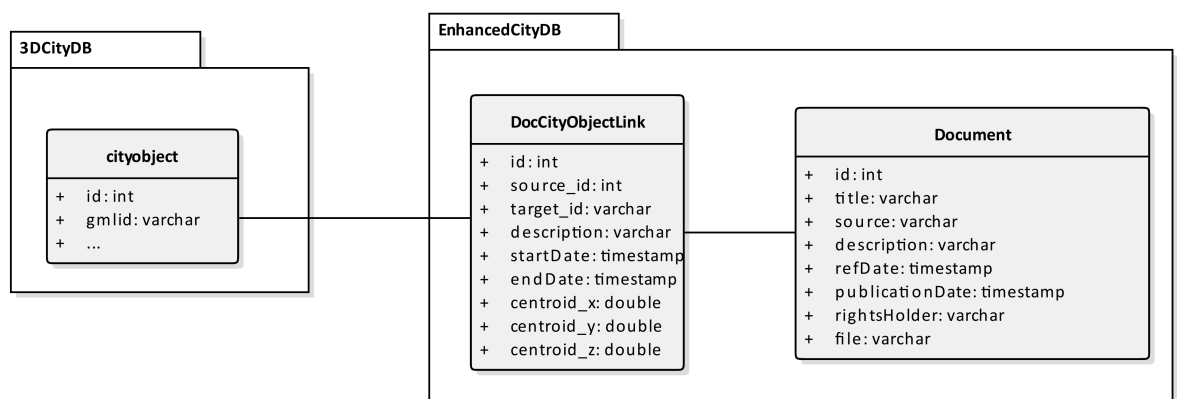


Figure B.1.: Physical model of *DocCityObjectLink* and *Multimedia Document*.

3D city objects are stored in the *3DCityDB*¹ database (its schema is described in the documentation available online²). Note that we use the 4.2 version of *3DCityDB* in this thesis. In this schema, the table *cityobject* stores city objects. Among its attributed, *gmlid* is an identifier of city objects that is guaranteed unique in a given city model. This *gml:id* is used for identifying the city objects in a link.

EnhancedCityDB is a database where *DocCityObjectLink* and *Multimedia Document* are stored. The *Multimedia Document* model is a first proposition including attributes inspired from the *DocumentObject* class proposed in [Sam+16]. This proposition is itself based on Dublin Core [Dub12]. A more elaborated model may however be proposed in the future. *DocCityObjectLink* stores links between city objects and multimedia documents. Its attributes include *description*, *startDate* and *endDate* which come from the inheritance of *Link*. In addition, it stores a *source_id* which is

¹<https://www.3dcitydb.org/3dcitydb/>

²<https://www.3dcitydb.org/3dcitydb/documentation/>

the *id* of *Multimedia Document* and a *target_id* which refers the *gmlid* of *cityobject*. While the *source_id* - *id* relationship is managed with a foreign key, the integrity of the *target_id* is verified before insertion in the database by a code living above these database and that can access them both. Finally, *DocCityObjectLink* also has three attributes *centroid_x*, *centroid_y* and *centroid_z* which indicate a position used for visual representation in *UD-Viz*. In particular, this position is the centroid of the linked city object, allowing to travel to this position when needed in the end-user application.

This physical model is a first prototype and may need to be redesigned in the future. More specifically, if links between other type of resources are implemented, some attributes of the links may be shared and therefore new tables holding these attributes may need to be created. In addition, multimedia documents may be stored outside of *EnhancedCityDB* in the future and referenced the same way than city objects.

Appendix C: Digital urban heritage tools analyzed for constructing DHAL

This appendix presents the fifty-four tools analyzed for constructing DHAL (table C.1). The tools selected for the usage of DHAL in the context of the Fab-Pat project (detailed in section 6.1.4) are the first twelve tools of table C.1 (also indicated in bold in the table).

Table C.1.: Short description of the fifty-four tools used for constructing DHAL.

Tool	Place	Description	URL	N°
Chapelle Royale of the Château de Versailles	Versailles, France	Successful virtual tour using 720° panoramic photos	http://www.chapelle.chateauversailles.fr/ [Last accessed: 4/2018]	1
Past virtual tour of the Château de Chenonceau	Chenonceau, France	Virtual tour of the Château de Chenonceau in the past combining 720° panoramic photos with a 3D model	http://www.ecliptique.com/chenonceau/index.html [Last accessed: 4/2018]	2
PastPort	Port Melbourne, Australia	Participatory platform for collecting local history that is geolocated on a map	http://www.citizenheritage.com/pastport-app/ [Last accessed: 4/2018]	3
Chapelle d'Ecouen Chantilly	Chapel of the Château d'Ecouen Chantilly, France	Virtual tour using 3D reconstructions and panoramic photos. Several eras available	http://musee-rennaissance.fr/sites/musee-rennaissance.fr/files/complement/chapelle/index.html [Last accessed: 4/2018]	4
Industrial Heritage of Lyon	Rhône, Lyon, France	Classical geolocation app for industrial heritage in Lyon	http://patrimoine-industriel-rhone-alpes.in-situ-concept.fr/ [Last accessed: 4/2018]	5

Tool	Place	Description	URL	N°
Sites and Cities	Left bank of the Rhône, Lyon, France	Geolocation of architectural heritage of Lyon's left bank on a Google map	https://www.google.com/maps/d/viewer?mid=1EnWlqcH8TRUtWkhfdqnv9navIVU&ll=45.7434189059372%2C4.895138719970646&z=13 [Last accessed: 4/2018]	6
Archivist	Alsace, France	Smartphone app combining geolocation of photos on a 2D map and augmented reality	https://www.facebook.com/larchiviste.eu/ [Last accessed: 4/2018]	7
Avignon 3D app	Avignon, France	3D reconstruction, geolocation, hotspots and augmented reality to reconstruct a damaged site	https://play.google.com/store/apps/details?id=com.gmt.avignon3d&hl=fr [Last accessed: 4/2018]	8
OhAhCheck (recently renamed "Sites et Cités Remarquables de France" [remarkable sites and cities of France])	France	Participatory geolocation app, augmented reality and photo reconnaissance to identify heritage sites in a participatory way. App has not been very successful	http://www.ohahcheck.com/ [Last accessed: 4/2018]	9

Tool	Place	Description	URL	N°
Izi.Travel	Large cities, world	Participatory, collaborative platform of audioguides on heritage that has been successful	https://izi.travel/fr [Last accessed: 4/2018]	10
Inventory of Monuments to the Dead	France and Belgium	Participatory inventory underway that has been fairly successful	https://monumentsmorts.univ-lille.fr/ [Last accessed: 4/2018]	11
Archi-Wiki	Strasbourg, France	Participatory site based on the “wiki” principle (collecting new information, correcting errors, etc.) that has had a little success	http://www.archi-wiki.org/ [Last accessed: 4/2018]	12
Chenonceau, 2D virtual tour	Château de Chenonceau, France	Virtual tour combining 720° photography with geolocation on a 2D map	http://www.podibus.com/Chenonceau_VR/#3 [Last accessed: 4/2018]	13
Immersive Journey: The Strasbourg Cathedral	Strasbourg Cathedral, France	Use of virtual reality to promote cultural heritage	http://www.voyageenimmersion.com/ [Last accessed: 4/2018]	14

Tool	Place	Description	URL	N°
Virtual tour of the Lyon Musée des Beaux-arts	Lyon, France	Virtual tour of a museum in Lyon using 720° panoramic photos	http://www.mba-lyon.fr/mba/sections/fr/musee-beau-art-lyon/visites-360/visites-panoramiques [Last accessed: 4/2018]	15
Virtual tour of the Reims Cathedral	Reims, France	Classical virtual tour of a religious site that still exists using 720° panoramic photos	http://www.cathedraledereims.fr/spip.php?article822 [Last accessed: 4/2018]	16
Virtual tour of the Abbey Church in Conques	Conques, France	Virtual tour combining 720° photography with geolocation on a 2D map	http://ecliptique.com/conques/ [Last accessed: 4/2018]	17
Virtual tour of Rodez	Rodez, France	Classical virtual tour with 720° photography used for many heritage sites	http://tourisme.grand-rodez.com/rodez/visites-virtuelles [Last accessed: 4/2018]	18
Virtual tour of several tourist sites in Lyon	Lyon, France	Typical virtual tours with 360° photography in Lyon	http://www.blog-in-lyon.fr/visite-virtuelle-lyon-decouvrez-lyon-360/ [Last accessed: 4/2018]	19

Tool	Place	Description	URL	N°
Lyon Patrimoine	Lyon, France	Virtual tours with 360° panoramic photos, videos of 3D models, documents, and tours of Lyon heritage	http://www.patrimoine-lyon.org/3d-plans-visites [Last accessed: 4/2018]	20
Versailles, 3D model	Versailles, France	Virtual tour of Versailles at several time periods from 1624 to 2012 using 3D models. Also available as a smartphone app	http://www.versailles3d.com/fr/decouvrez-les-maquettes-3d/ [Last accessed: 4/2018]	21
3D tours of the gardens of Versailles	Versailles, France	Virtual tour using 3D models of the gardens of Versailles from the early 2010s	http://www.chaostoperfection.com/ [Last accessed: 4/2017]	22
In the walls of the Casbah	Algiers, Algeria	Successful virtual web-documentary tour	http://casbah.france24.com/ [Last accessed: 4/2018]	23
Monluc, multiple memories	Lyon, France	(Successful) web-documentary virtual tour attempting to add an (unsuccessful) participatory aspect about Lyon.	http://www.patriminum.fr/montluc/ [Last accessed: 4/2018]	24

Tool	Place	Description	URL	N°
Goldsmith's Bench	Château d'Ecouen, France	Web-documentary video tour using 3D as well as traditional informational content on a technical subject	http://musee-rennaissance.fr/sites/musee-rennaissance.fr/files/complement/bancondorfevre/index2.html [Last accessed: 4/2018]	25
MobiTour app	France	Classical geolocation heritage app available for several French cities	http://www.mobitour.fr/ [Last accessed: 4/2018]	26
Cityscape, architectural heritage	Lyon, France	Classical geolocation app for modern architecture in Lyon	http://cityscape.fr/fr [Last accessed: 4/2018]	27
citymap2go	World	Tour app for large cities by geolocation of heritage that has had great success around the world	http://www.ulmon.com/#get-the-app [Last accessed: 4/2018]	28
Heritage tour of La Rochelle	La Rochelle, France	Classical geolocation heritage app	https://play.google.com/store/apps/details?id=fr.larochelle.visitepatrimoine&hl=fr [Last accessed: 4/2018]	29
Bridges of the Rhône	Lyon, France	Classical geolocation app for the heritage of bridges of the Rhône	http://ponts-rhone-alpes.in-situ-concept.fr/ [Last accessed: 4/2018]	30

Tool	Place	Description	URL	N°	
CartoBleuet	Bleuets neighbourhood, France	neighbourhood, Créteil, France	Geolocation of immaterial heritage with the collaboration of neighbourhood residents	http://plaine-centrale.webgeoservices.com/mapviewers/586/?format=browser [Last accessed: 4/2018]	31
Geocaching	World		Popular worldwide game combining geolocation, research and discovery of heritage	https://play.google.com/store/apps/details?id=com.groundspeak.geocaching.intro&hl=fr [Last accessed: 4/2018]	32
TerraAdventura	Limousin, France		Use of geocaching by institutions to promote heritage	http://www.terra-aventura.fr/fr/ [Last accessed: 4/2018]	33
Lyon, 1939-1945: History in the City	Lyon, France		2D geolocation of important events from World War II in Lyon	http://cartes.lyon.fr/1939-1945/ [Last accessed: 4/2018]	34
Traboules Tour app	Lyon, France		Smartphone app combining geolocation of photos on a 2D map and augmented reality	http://www.traboules-lyon.fr/ [Last accessed: 4/2018]	35
Perpignan 3D app	Perpignan, France		2D geolocation, augmented reality, 3D models, photos, hotspots, etc. for discovering several sites in Perpignan	https://itunes.apple.com/fr/app/perpignan-3d/id1031634198?mt=8 [Last accessed: 4/2018]	36

Tool	Place	Description	URL	N°
Capture the Museum	Edinburgh Museum, Scotland	Game combining geolocation and augmented reality created by an institution (museum) to promote its collections	http://www.capturethemuseum.com/ [Last accessed: 4/2018]	37
Random mediation of heritage of southern Paris	Paris, France	Geolocated audio tour where several factors (localization, speed of movement, path taken, etc.) influence the information provided during the tour	http://www.heritage-experience.fr/ [Last accessed: 4/2018]	38
Audio tour of the Château de Versailles	Versailles, France	Geolocated audio tours of the Château de Versailles	https://play.google.com/store/apps/details?id=com.sycomore.chateaudeversaille.activity&hl=fr [Last accessed: 4/2018]	39
Audio tour of the gardens of Versailles	Versailles, France	Geolocated audio tours of the gardens of Versailles	https://play.google.com/store/apps/details?id=com.orange.versaillesjardins&hl=fr [Last accessed: 4/2018]	40
GuidoGo	Europe	Participatory, collaborative platform (mobile app and web) of audioguides on heritage that has been fairly successful in France	https://www.guidigo.com/ [Last accessed: 4/2018]	41

Tool	Place	Description	URL	N°
ASK Brooklyn Museum	Brooklyn Museum, USA	Use of geolocation by a museum to replace the “traditional guide” with audioguides	https://play.google.com/store/apps/details?id=ask.brooklynmuseum.org&hl=frApplication [Last accessed: 4/2018]	42
Participatory inventory of rammed earth buildings in Lyon	Lyon area	Participatory inventory of buildings made of rammed earth in the Lyon area	http://patrimoine-terre-lyonnais.patrimoineaurhalpin.org/ [Last accessed: 4/2018]	43
Architectural Inventory of Villeurbanne	Villeurbanne, France	Participatory inventory underway in Villeurbanne	http://lerize.villeurbanne.fr/vie-du-rize/inventaire-participez/#more-3341 [Last accessed: 4/2018]	44
Aïoli	World	Platform for adding semantic annotation or additional resources (texts, images, videos, etc.) to heritage objects	http://www.aioli.cloud/en/ [Last accessed: 4/2018]	45
Clameur	World	Participatory platform for gathering and sharing material and immaterial heritage that has not been very successful	http://www.clameurs.fr/presentation/ [Last accessed: 4/2018]	46

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Memoirs of the 4th district of Lyon	4th district of Lyon, France	Sharing immaterial heritage through collaborative geolocation of anecdotes in the 4th district of Lyon	https://www.google.com/maps/d/viewer?mid=1qqYjXMmegn-mjMEXuPCnyZjyyPs&ll=45.78063389031291%2C4.819135412658625&z=14 [Last accessed: 4/2018]	47
Troubadour Story	Lyon, France	Participatory and collaborative platform of geolocated audioguides on the heritage of Lyon that has not been very successful	http://www.troubadourstory.fr/ [Last accessed: 4/2018]	48
Geolocation of photos of marius.marseille.fr	Marseille, France and surrounding towns	Geolocation of old photos on a 2D map. Overlay of old maps. Participatory functionalities are planned	http://beaubiat.fr/geolocaliserMarius/#12/43.2967/5.3631 [Last accessed: 4/2018]	49
Lyon in 1700	Lyon	Faithful 3D reconstruction of the city of Lyon in 1700 with clarification of the process of setting up the tool	http://lyon-en-1700.blogspot.be/ [Last accessed: 4/2018]	50
Mysteries in Versailles	Versailles	Free geolocated game to explore the Château de Versailles and its gardens in a fun way	https://play.google.com/store/apps/details?id=com.furetcompany.versailles&hl=fr [Last accessed: 4/2018]	51

Tool	Place	Description	URL	N°
Inside the Stones	England	Virtual tours of Stonehenge through classical images or panoramic photos containing hotspots that give access to multimedia (videos, texts, images, etc.)	http://www.english-heritage.org.uk/visit/places/stonehenge/history/stonehenge360/ [Last accessed: 4/2018]	52
Sondaqui	Aquitaine region, France	Presentation of the immaterial heritage of the Aquitaine region through lists, 2D geolocation and thematic groupings of media	http://www.sondaqui.com/ [Last accessed: 4/2018]	53
Survey of London	Neighbourhood of Whitechapel, London	Participatory tool containing a lot of multimedia (photos, text documents, videos, audio, etc.) added by historians, residents and people interested in the location. The documents are geolocated on a 2D map	https://surveyoflondon.org/ [Last accessed: 4/2018]	54

