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Integrating multimedia documents and time-evolving 3D city models for web visualization and navigation

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Abstract

Many geographic features such as 3D city models, real-time sensor data or multimedia documents (photo, audio, video, etc.) are nowadays available for describing urban areas. These heterogeneous geographic features are multidimensional (spatial, thematic and temporal), can have multiple representations (text, iconography, etc.) and can be modeled using diverse formats. Browsing and crossing these features can help analysing, understanding past and present and planning future evolution of cities. Furthermore, implementing it in a web context allows sharing and enriching them in a collective way. In this article, we propose a new generic model (*GenLinkable*) for integrating such features. We also propose the *Gen4DCity-Doc* model which specifies *GenLinkable* to integrate multimedia documents and time-evolving 3D city models for web visualization and navigation. *Gen4DCity-Doc* extends previous research results by integrating new resources describing cities (multimedia documents). *Gen4DCity-Doc* is implemented in a web prototype based on a 4-tier architecture using and enhancing open source software and standards. Finally, we also demonstrate that these models open new navigation possibilities in 3D city models and in multimedia documents through a 3D web interface, which is a current challenge, especially to help researchers in urban history.

Keywords 3D city models; Multimedia documents; Links; Linkable objects; Geospatial; Data models

1 Introduction

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 destroyed, parks are created, etc. Throughout these modifications, cities undergo horizontal and vertical sprawls. In this context, analysing and understanding the city, its evolution and how people live in it becomes a central issue.

3D city models provide digital representations of urban areas with 3D geometric, thematic and geo-referenced elements at different scales. These elements are 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. (Biljecki et al., 2015). Furthermore, they have recently been enhanced to time-evolving 3D city models (Chaturvedi et al., 2017; Jaillot, Servigne, et al., 2020; Samuel et al., 2018; Samuel et al., 2020). In parallel, the number of 3D geovisualisation applications available have been growing during the past years, some of them even allowing visualization and navigation in 3D city models or in time-evolving 3D city models (Jaillot, Servigne, et al., 2020). In addition, there is an increasing need for sharing and enriching these resources in a collaborative manner (Jaillot, Istasse, et al., 2020; Münster et al., 2020) which leads to working in a web context.

However time-evolving 3D city models alone are not enough to understand cities and their evolution. Other features¹ from a variety of sources can provide complementary elements leading to more complete analyses and better comprehension of cities. Multimedia documents for instance are key materials 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. also bear numerous and valuable information. Gathering, sharing and exploiting documents contributes to preserving and developing common knowledge. They describe cities, their evolution and how people live (in) them. Combined with the evolution of the city, they also help to answer questions such as *How was the city at a given time and what evidences that can prove it ?* Furthermore, in (Münster et al., 2020), they 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 document *navigation* (i.e. access, querying).

Several contributions have been proposed for integrating multimedia documents into 3D urban environment but they mainly focus on an integration at the visual level (Brivio et al., 2013; Dewitz et al., 2019; Schindler & Dellaert, 2012; Snavely et al., 2006). However, this choice constrains the integration of multimedia documents to iconographies which are only a subset of available multimedia documents. In a more general way, we must propose methods and models allowing the integration of other geographic features.

In this article, we provide the following contributions to address these challenges:

- **Developing a generic conceptual model** for linking **features** (*GenLinkable* model).
- **Specifying** this model for **multimedia documents** and **time-evolving 3D city models** integration (*Gen4DCity-Doc*).
- **Implementing** a proof of concept for multimedia documents and 3D city models navigation based on open standards and software, along with a link to a detailed procedure to reproduce the experiments.

Before going in depth with these contributions, we first start with a short background presentation of our previous work with 3D city models, time-evolving 3D city models and multimedia documents in section 2, that we propose further in this article. Then, we present a state of the art for the integration of multimedia documents in 3D urban environments in section 3. After that, we present our first model contribution: *GenLinkable* in section 4.1. In section 4.2, we first briefly describe the concepts of *Gen4DCity* which we extend in this work (section 4.2.1) and we present our other contribution at the model level: *Gen4DCity-Doc* (section 4.2.2). Section 5 contains a description of the proposed implementation. We present the functionalities of this implementation and examples of usage for navigating in a documented and temporal 3D city in section 6. We finish the article with a conclusion and possible future work in section 7.

2 Background

We present some previous work from our team on time-evolving 3D city models and multimedia documents that we will extend in this article.

CityGML (Kolbe, 2009), proposed by the Open Geospatial Consortium (2012) is currently the most popular standard for modelling urban landscapes. It represents what is commonly named 3D city models with structured thematic and geometric models. However, while it has been widely accepted by the geospatial community and by data producers (many big cities provide their 3D city model in CityGML: e.g. Lyon², Berlin³ or New York⁴), CityGML is focused on 3D cities storing and exchange and it has not been designed for efficient visualization and navigation on the web (Kolbe, 2009), which is one of our requirements. Other formats like CityJSON (Ledoux et al., 2019) are now appearing in the City information models community. However, it is still not accepted as a standard.

¹A feature is defined as "abstraction of real world phenomena." by the International Standard Organisation (ISO) (International Organization for Standardization, 2008) and by the Open Geospatial Consortium (OGC) <https://www.opengeospatial.org/ogc/glossary/f>

²<https://data.grandlyon.com/jeux-de-donnees/maquettes-3d-texturees-a-commune-arrondissement-2009-2012-2015-metropole-lyon/info>

³<https://www.businesslocationcenter.de/en/economic-atlas/download-portal/>

⁴<https://www1.nyc.gov/site/doitt/initiatives/3d-building.page>

Recently, two specifications have been proposed for big and heterogeneous 3D geospatial datasets visualization on the web: I3S (Open Geospatial Consortium, 2017) and 3D Tiles (Open Geospatial Consortium, 2019). They are also based on thematic and geometric models but allow organizing data according to spatial index and are based on web-friendly and efficient representations (JSON and binary). Given the conceptual similarities between these standards, we proposed a generic conceptual model for the visualization of 3D city model on the web that we named *Gen3DGeo* in Jaillot, Servigne, et al. (2020). This model allows working 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 their underlying concepts. In Jaillot, Servigne, et al. (2020), we also proposed *Gen4DCity* which extends *Gen3DGeo* with a formalization of the temporal dimension of cities. This model allows visualizing time-evolving 3D city models on the web. We briefly present the concepts of *Gen4DCity* in section 4.2.1. In Jaillot, Servigne, et al. (2020), we have also proposed logical and physical models and an implementation allowing to visualize cities evolution in time. Figure 1 shows an example of visualization of the evolution of a district of the city of Lyon. In this figure, green indicates buildings that are being constructed, yellow ones are being modified and red ones are being destroyed.



Figure 1: 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 the implementation of *Gen4DCity*.

In Samuel et al. (2016), we proposed an extension to CityGML for multimedia documents. This contribution is based on standards: CityGML for the 3D city model and Dublin Core (Dublin Core Metadata Initiative, 2012; Weibel, 1997) for multimedia documents. In addition, the relation between documents and city objects is materialized with an association class 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 integrating multimedia documents with concepts describing the temporal dimension of cities.

Our purpose in this article is twofold. First, we propose general concepts and a conceptual model (*GenLinkable*) for integrating features in general (e.g. time-evolving 3D city models and multimedia documents but it could also be used for sensors for instance) in section 4.1. Then, we specify this model for multimedia documents and time-evolving 3D city models integration by extending *Gen4DCity* in section 4.2.

3 Related Work

We identified two main approaches for the integration of multimedia documents to 3D city models shown in Figure 2. 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 3.1. The second category of approaches, allowing thematic association of multimedia documents and 3D city models, is presented in section 3.2.

3.1 Methods based on spatial integration and navigation

The first category of approaches consists of 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 underlying 3D model. This placement of documents 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, Brivio et al. (2013) and Snavely et al. (2006) propose systems for browsing large collections of photographs placed in a 3D scene and calibrated over the 3D models they represent. 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 ?*

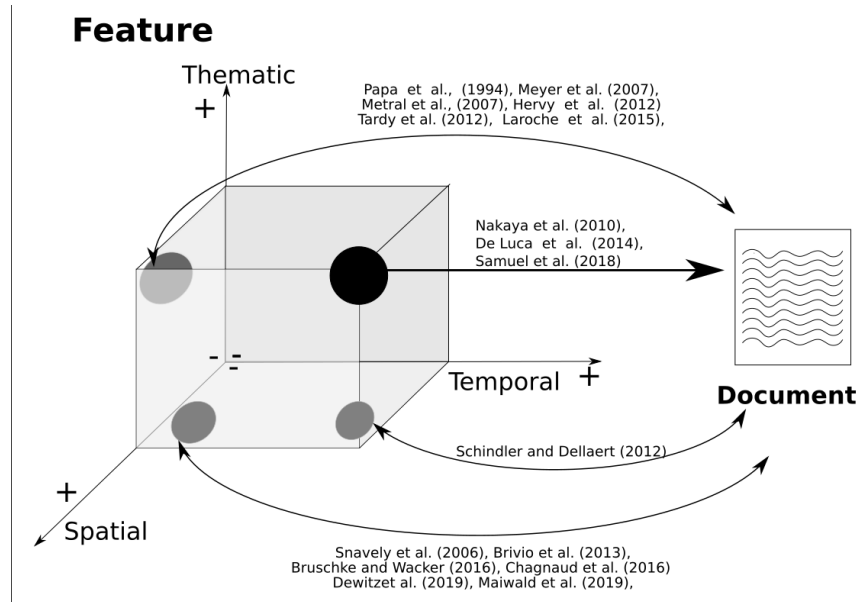


Figure 2: Methods based on spatial integration, navigation and thematic association. Special focus has been made on works linking documents and the three features.

Nakaya et al. (2010) 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 (2012) propose methods to reference images spatially and temporally and to automatically reconstruct 3D models represented by these images. Then navigation through time is possible to see the evolution of the 3D model and documents geolocated in the 3D scene. This method is however not based on standards and has been experimented on small spatial areas.

Bruschke and Wacker (2016) designed a system for 3D reconstruction projects allowing the integration of multimedia documents sources by visualizing them inside the 3D reconstructed scene. Similarly to Dewitz et al. (2019), Maiwald et al. (2019), and Schindler and Dellaert (2012) propose methods 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. They also allow displaying quantitative information about the multimedia documents such as the number of images in a certain area or heat maps based on images orientations. Chagnaud et al. (2016) 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 of 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 based on a snapshot model (representing static states at different timestamps) (Siabato et al., 2018) while graph-based models (representing static and changing states) provide more information about the evolution of cities and have been privileged these past years for 3D

city models (Chaturvedi et al., 2017; Jaillot, Servigne, et al., 2020; Renolen, 2000; Samuel et al., 2018; Samuel et al., 2020). Moreover, they do not allow navigating 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 (Busayarat et al., 2010; De Luca, 2014; De Luca et al., 2011; Pamart et al., 2019). These contributions are summarized in De Luca (2014). 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 Busayarat (2010), Busayarat et al. (2010), De Luca et al. (2011), and Pamart et al. (2019). These propositions 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 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 implemented in the NUBES (Stefani et al., 2010) and in the Aioli (Manuel, 2016) platforms, long with the temporal dimension of architectural models as well as multimedia documents. All these contributions permit the integration of images and 3D and thematic architectural elements, based on spatial criteria. They go further than the methods presented 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. few buildings) and are not based on standards which is one of our objectives to ensure interoperability with other systems.

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 identified early in Meyer et al. (2007). They propose a model where documents and archaeological objects are associated for designing a web based information system for managing and disseminating 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. In a similar fashion, Laroche et al. (2015) propose a model for associating documents and 3D objects representing the harbor of Nantes in 1900. However, these two propositions 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 that such models do not allow to fully grasp the evolution of city objects.

Hervy et al. (2012) discusses the harmonization of the Nantes in 1900 project (Laroche et al., 2015) with the Virtual Leodium project (Pfeiffer et al., 2013) (which proposes a similar approach). However, this discussion is more focused on proposing a general process for the acquisition of 3D models of historical sites rather than on the integration of their respective models for documents and 3D objects. In addition, while Pfeiffer et al. (2013) 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.

Some methods based on semantic web technologies for creating links between multimedia documents and 3D city models have also been proposed (Métral et al., 2007; Tardy et al., 2012). 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 allows deriving 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 (Papa et al., 1994). 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 integration. However, their proposition is limited to multimedia documents.

3.3 Summary

Among the propositions for multimedia documents and 3D objects integration, none fulfills all our objectives at the same time. They indeed use one or more of the following:

- 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 have been considerably explored, propositions for thematic and temporal integration and navigation of multimedia documents and 3D city models are still not fully satisfactory. However, the propositions of Samuel et al. (2016) (because it allows thematic integration of multimedia documents and 3D city models) and of Papa et al. (1994) (because of the conceptual similarities and propositions) are the closest to meeting our needs. We will base our data models to integrate multimedia documents to 3D city models (presented in section 4) on these methods.

4 Multimedia documents and time-evolving 3D city models integration

An implementation and application of these contributions are presented in section 5.

4.1 General concepts

We introduce two concepts for features integration: **Linkable Feature** and **Link** (specifying the concepts proposed in Papa et al. (1994)). After recalling the definition of feature, we propose a definition of these concepts.

Definition 4.1. Feature: Abstraction of real world phenomena. Sources: International Standard Organisation (ISO) (International Organization for Standardization, 2008) and Open Geospatial Consortium (OGC)⁵

Definition 4.2. Linkable Feature: A linkable feature is an abstract data type allowing the operation being linked to:

Definition 4.3. 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 3. We name this model **GenLinkable**. We define the *Link* as a template class⁶ with two template parameters : *A* and *B*. This notation allows expressing 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 us take an information system that manages sensor data streams, multimedia documents and 3D city models. This model allows limiting 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 the management of multiple relations between features. *A* and *B* are *Linkable Features*.

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

⁶<https://www.uml-diagrams.org/template.html>

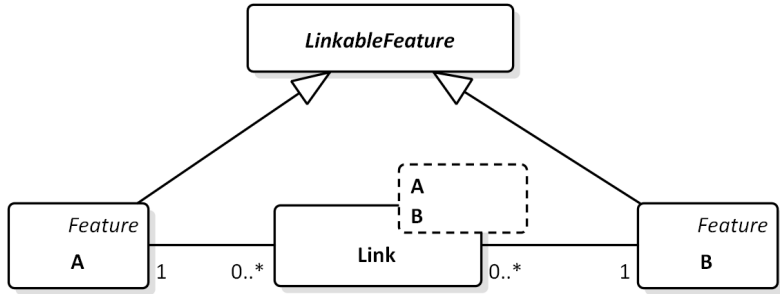


Figure 3: **GenLinkable**: Conceptual model for linking features.

We propose a logical model of *Link* in figure 4. 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 period.

Figure 4 presents the logical model of the *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.

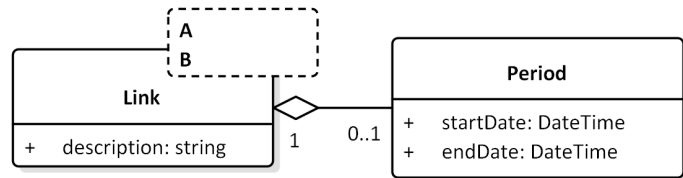


Figure 4: Logical model of *Link*.

This model proposes top-level concepts, providing a way to integrate features in the spatial, temporal and thematic dimension, without interfering with their representation in their respective formats (Figure 5). A letter, for example may have a location or refer to many locations in the text.

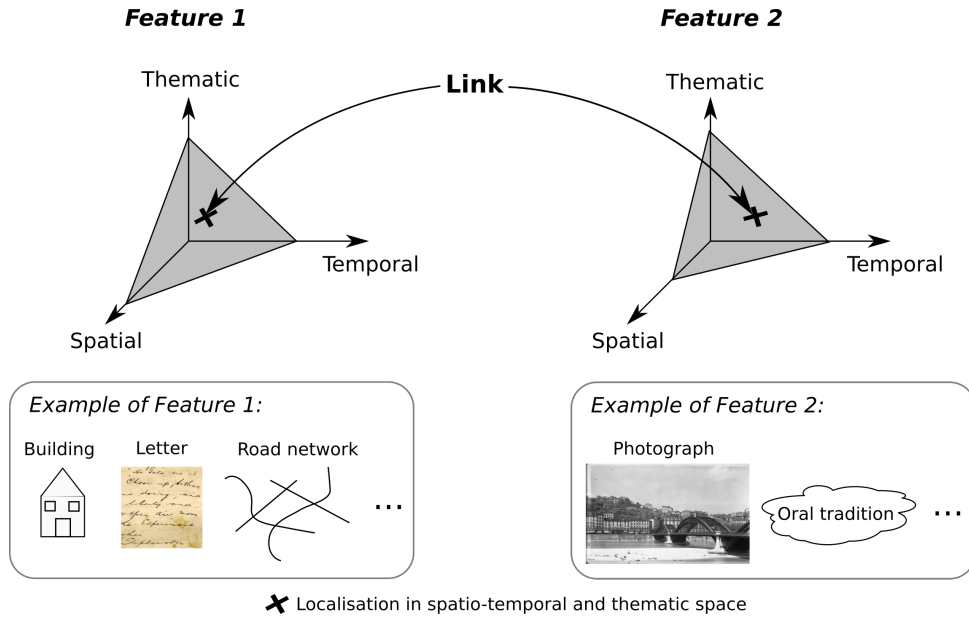


Figure 5: Conceptual representation of features linking in their spatio-temporal and thematic space.

In section 4.2, we specify this model for time-evolving 3D city models and multimedia documents integration.

4.2 Specification for multimedia and time-evolving 3D city models

In this section, we specify *GenLinkable* into the **Gen4DCity-Doc** model for the integration of time-evolving 3D city models and multimedia documents for their visualization and navigation on the web. It shows the applicability of *GenLinkable* and it extends previous research: the *Gen4DCity* model (that we introduced in Jaillot, Servigne, et al. (2020)). Figure 6 presents **Gen4DCity-Doc**: a generic conceptual model for time-evolving 3D city models and multimedia documents integration for their visualization and navigation on the web. *Gen4DCity* is represented in white and green where white concepts correspond to the 3D part of city models and green concepts represent their temporal dimension. The blue concepts concern the integration of multimedia documents to *Gen4DCity* by specifying *GenLinkable*. For a better understanding of our proposition, we first provide a brief description of *Gen4DCity* in section 4.2.1. In section 4.2.2, we present the improvements of this model for the integration of multimedia documents.

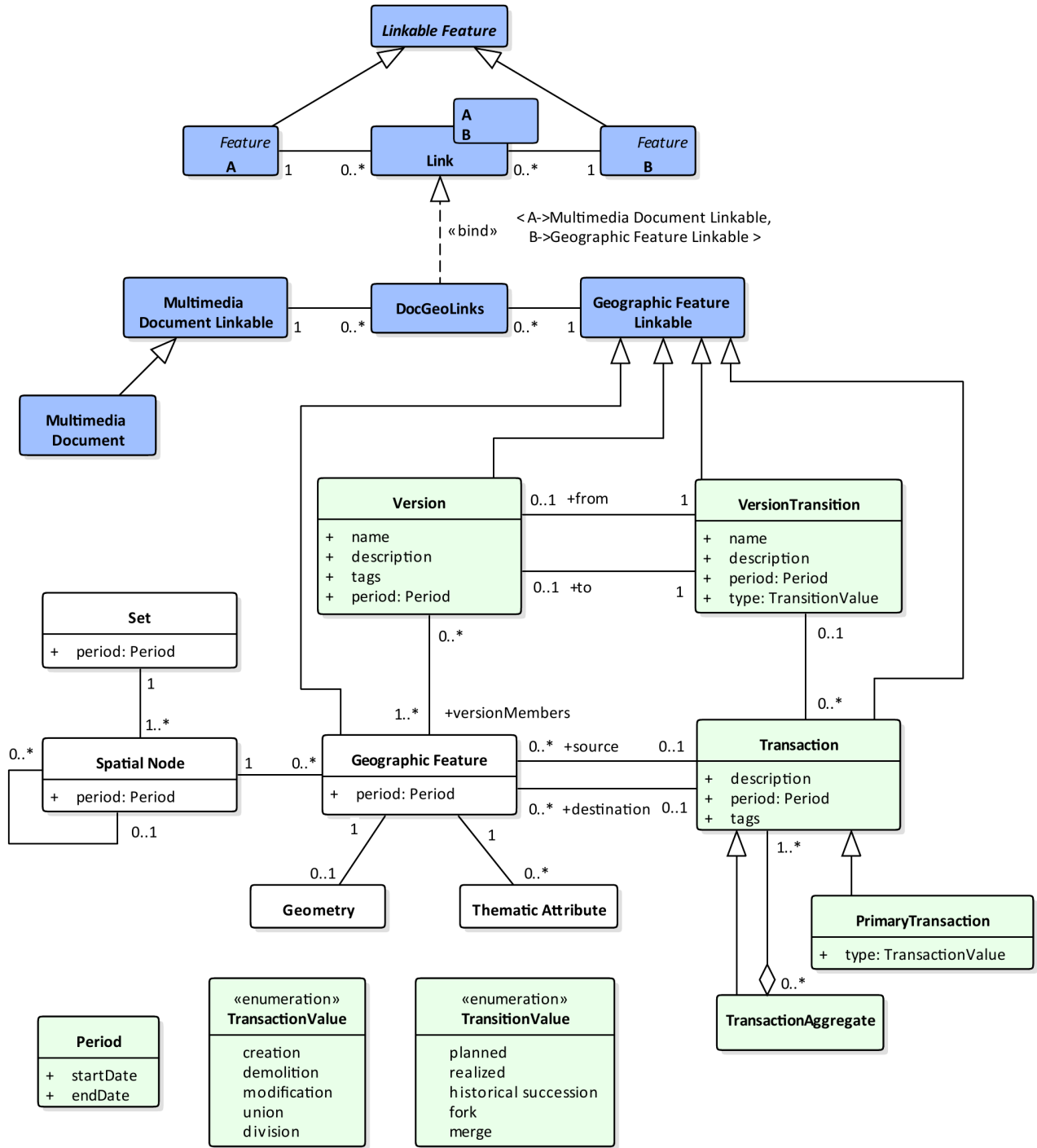


Figure 6: **Gen4DCity-Doc**: Generic conceptual model integrating time-evolving 3D city models and multimedia documents. This model extends *Gen4DCity* (Jaillot, Servigne, et al., 2020) with *GenLinkable* (from figure 3) and with *Multimedia Documents*. *Gen4DCity* is represented in white and green where white concepts correspond to the 3D part of city models and green concepts represent their temporal dimension. The blue concept concerns the integration of multimedia documents to *Gen4DCity* by specifying *GenLinkable*.

4.2.1 Gen4DCity: a generic model for delivering time-evolving 3D city models for web visualization

We proposed *Gen4DCity* (in white and green in figure 6) in a previous work (Jaillot, Servigne, et al., 2020). We detail some of its concepts here for a better understanding of the improvements made in this article. *Gen4DCity* is a generic conceptual model for delivering time-evolving 3D city models for their visualization on the web. The part in white is an abstraction (and a shared representation) of the two main current standards designed for delivering 3D geographic data for their visualization on the web (3D Tiles and i3s, see section 2). *Geographic features* are defined as "representation of real world phenomenon associated with a location relative to the Earth" by the International Standard Organization (ISO) (International Organization for Standardization, 2008) and by the Open Geospatial Consortium⁷ (OGC). In our context, it represents elements of cities such as houses, bridges, parks, etc. *Geographic features* generally have a *geometry* (e.g. a 3D model) and *thematic attributes* (e.g. name, owner, usage, etc.). These *geographic features* are organized in an index (e.g. quadtree) that is represented by the *Spatial node* concept and by its recursive association. The top level object is named *Set*.

The temporal formalization has been proposed in Jaillot, Servigne, et al. (2020) and is based on Chaturvedi et al. (2017) and Renolen (2000). A period attribute (a temporal period with a start and an end date) have been added to *geographic features*, *spatial nodes* and *set* in order to add a temporal dimension to them. Other concepts have also been added to describe the temporal dimension of cities. First, *transactions* describe a changing state between two geographic features (e.g. renovation of a bridge, facade restoration, etc.). An example of a transaction between two buildings is presented in figure 8. *Primary transactions* can be of five types (creation, demolition, modification, union and division, defined in *TransactionValue*) and more complex ones can be formed with the *TransactionAggregate* concept.

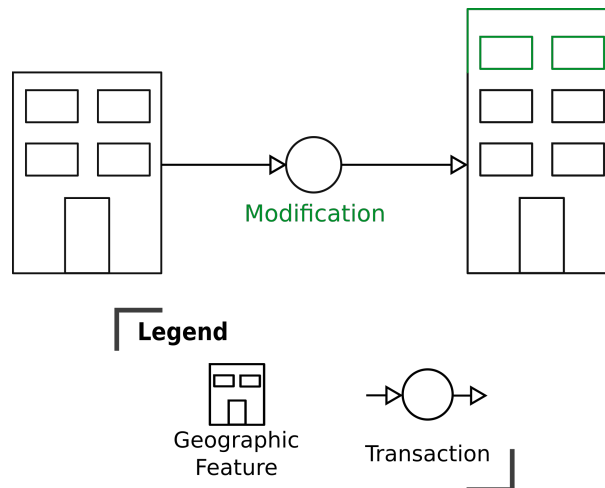


Figure 7: Example of transaction between two geographic features

Two other concepts describe changes in the city but at another spatial scale: *versions* and *version transitions*. Versions are a collection of *geographic features*. They can be used to define specific versions of a construction or renovation project for a district for instance. Similarly, *Version transitions* describe changes between two *Versions* and are a collection of *transactions* (the transactions between the geographic features of two versions). *Versions* and *Version transitions* may also be used to concurrent possibilities of evolution of a city (e.g. different hypotheses of evolution in the past proposed by different historians).

For more details on *Gen4DCity*, we invite the reader to see our previous work (Jaillot, Servigne, et al., 2020) where it is fully described and implemented. In section 4.2.2, we extend this model for the integration of multimedia documents.

⁷<https://www.opengeospatial.org/ogc/glossary/g>

4.2.2 Gen4DCity-Doc: a generic model for time-evolving 3D city models and multimedia documents integration

By specifying the *GenLinkable* model (presented in section 4.1), we propose to integrate multimedia documents to time-evolving 3D city models (figure 6). *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 expressing which concepts from the multimedia documents model and from *Gen4DCity* are linkable. We represent the multimedia documents model by the *Multimedia Document* entity, as specified in section 5. 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 evolve in time for instance. Figure 8 shows an example of links between multimedia documents, geographic features and transaction.

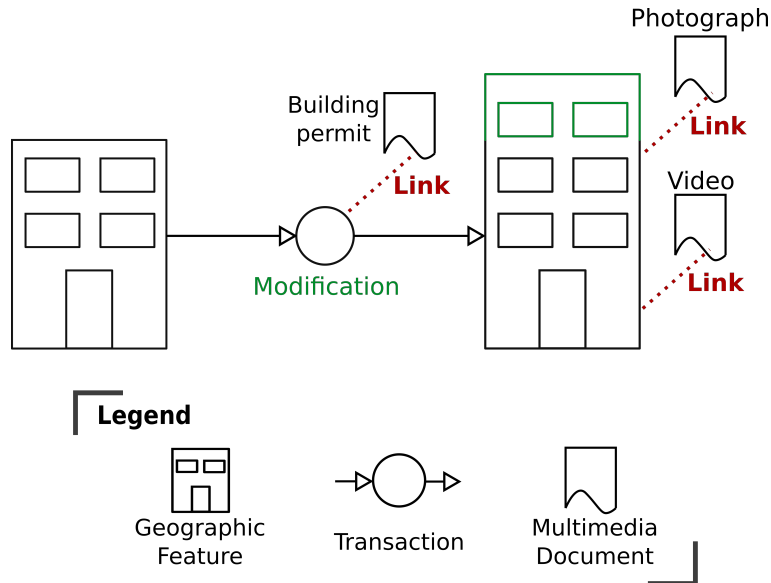


Figure 8: Example of links between multimedia documents and geographic features and transaction.

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.

5 Implementation

We start by proposing a logical and a physical model of *Gen4DCity-Doc* that also specifies the scope of our implementation. Then, we present the software architecture of UD-SV (Urban Data Services and Visualisation) in which we implemented the propositions of this article.

5.1 Logical and physical models of Gen4DCity-Doc

The proposed implementation focuses on multimedia documents and city objects integration as a first step. Figure 9 is a logical model showing the scope of the implementation and the relation between the implemented classes and *Gen4DCity-Doc* (figure 6).

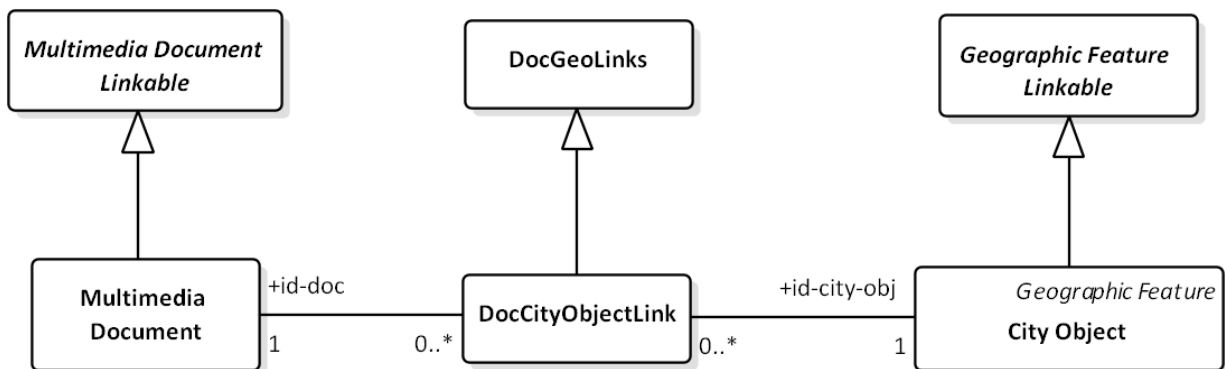


Figure 9: Logical model of the implemented link between multimedia documents and city objects.

City object is a *Geographic Feature*. *DocCityObjectLink* is the entity describing links between *Multimedia Document* and *City Object*. A physical model is presented in figure 10.

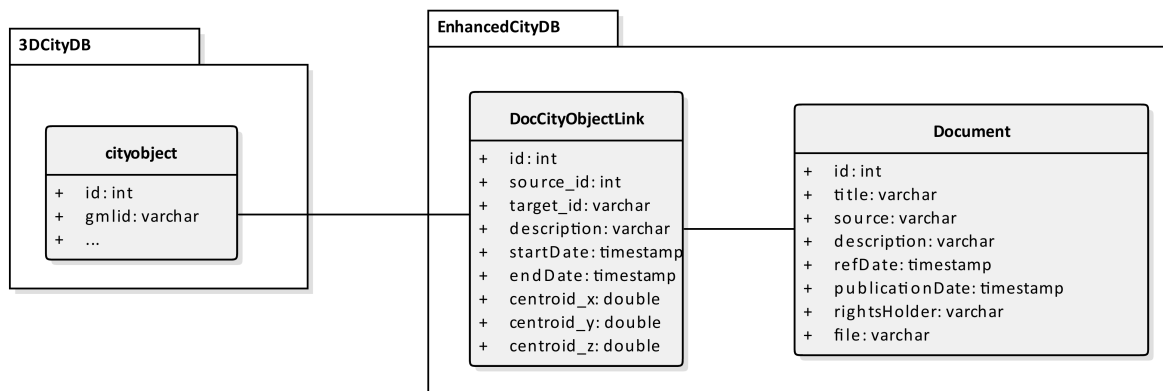


Figure 10: Physical model of *DocCityObjectLink* and *Multimedia Document*.

3D city objects are stored in the *3DCityDB*⁸ database (its schema is described in the documentation available online⁹). In this schema, the table *cityobject* stores city objects. Among its attributes, *gmlid* is an identifier of city objects that is guaranteed to be 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 Samuel et al. (2016) This proposition is itself based on Dublin Core (Dublin Core Metadata Initiative, 2012). 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 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 the web client. In particular, this position is the centroid of the linked city object, allowing end users to travel to it when needed in the 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

⁸<https://www.3dcitydb.org/3dcitydb/>

⁹<https://www.3dcitydb.org/3dcitydb/documentation/>

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.

The models proposed in this article and this implementation are modular. Therefore, the same process could be applied to other features (e.g. transactions). In section 5.2, we present the evolution of the prototype architecture to integrate multimedia documents and links. Then, we demonstrate how the contributions of this article enhance navigation in multimedia documents and 3D city models.

5.2 An open source and web-based implementation

We implemented our proposition in the UD-SV project. The software architecture of UD-SV is presented in figure 11. The components that have been modified or created for the implementation of the proposition of this article are highlighted in green.

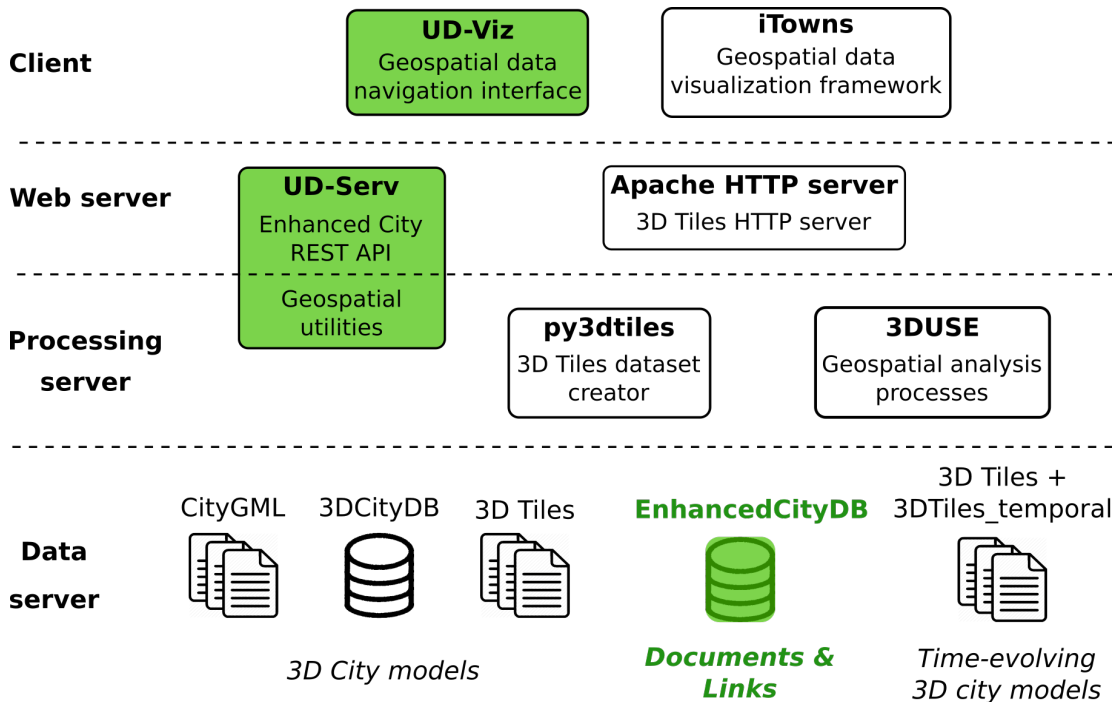


Figure 11: Software architecture of the web-based prototype for multimedia documents and 3D city objects linking and navigation. The components that have been modified or created for the implementation of the proposition of this article are highlighted in green.

UD-SV architecture is composed of four layers: the data server layer, the processing server layer, the web server layer and the client layer. In the data layer there are 3D city models as well as time-evolving 3D city models and a database storing multimedia documents and links (*EnhancedCityDB*) following the physical model presented in figure 10. The processing layer is composed of py3dtiles, 3DUSE and of a part of *UD-Serv*¹⁰ (some geospatial utility tools). 3DUSE mainly contains geometric and geographic processes such as detecting geometric changes between different vintages of a city (Pédrinis et al., 2015) or as providing a sunlight analysis of a city (Jaillot et al., 2017). Py3DTiles allows converting geospatial data (e.g. from a 3DCityDB database or from LAS files) into the 3D Tiles format. In our case, it allows us to create 3D City models and time-evolving 3D city models in the 3D Tiles format. The web server layer is composed of two services: *UD-Serv* (for documents and links) and an Apache HTTP server (for serving city models). *UD-Serv* allows making *CRUD* (Create, Read, Update, Delete) operations on multimedia documents and links. It is based on Object-Relational Mapping (ORM) and can be installed as a docker container. The client layer is composed of *UD-Viz*¹¹ which is based on the geospatial data

¹⁰<https://archive.softwareheritage.org/browse/origin/https://github.com/MEPP-team/UDV-server/directory/>

¹¹<https://github.com/MEPP-team/UD-Viz>

visualization framework *iTowns*¹². *iTowns* allows visualizing 3D city models while *UD-Viz* takes care of the visualization of the temporal dimension and of documents and links.

6 Results and usage

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)¹³.

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 12. 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 filtering 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 who 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.

¹²<https://archive.softwareheritage.org/browse/origin/https://github.com/iTowns/itowns/directory/>

¹³<https://patrimoine.auvergnhonealpes.fr/>

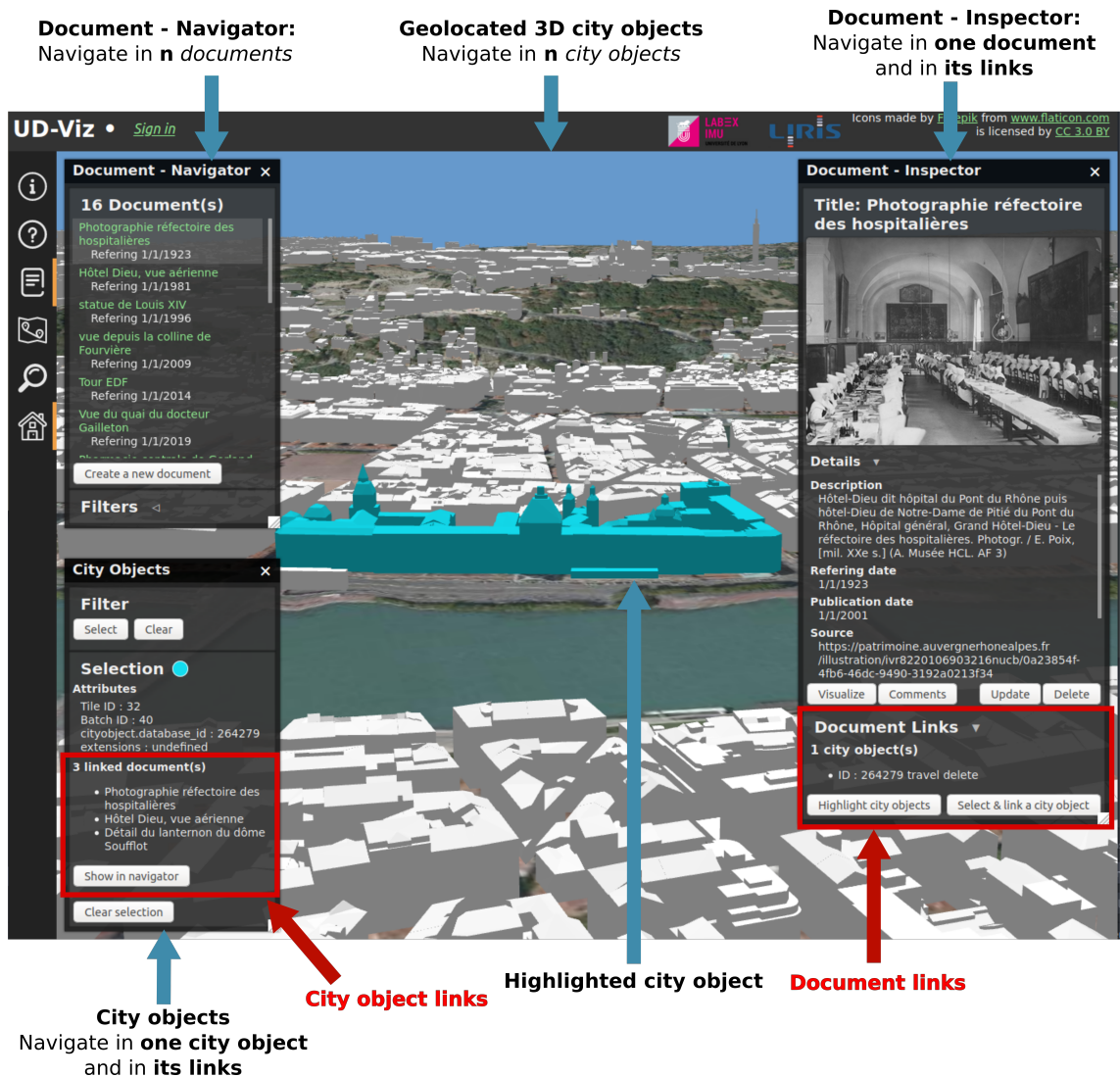


Figure 12: Interface and main components of the prototype for linking and navigating multimedia documents and city objects.

One technical question concerns the visual representation of links in the 3D scene since they do not have an intrinsic geometry. One possibility is to assign them one. Previous work has been undertaken in that direction (Chagnaud et al., 2016), where multimedia documents are displayed as billboards placed over the city element they reference, and links are represented by lines between multimedia documents and city objects. Some tests have been done to provide a document image in the 3D scene. We superimpose the image in an appropriate place in the HTML context. Rotating in the 3D scene however does not imply a rotation on the image. 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 (Robinson, 2011; Trapp, 2013) 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. ColorBrewer¹⁴) in further developments.

Links allow navigating from documents to city objects and from city objects to documents. In addition, they allow associating documents that cannot be integrated to city objects at the visual level.

¹⁴<http://colorbrewer2.org/>

Figure 12 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 12). 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 12). 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 12). 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 these 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 13 shows an example of such a filter which highlights the city objects with at least one linked document.

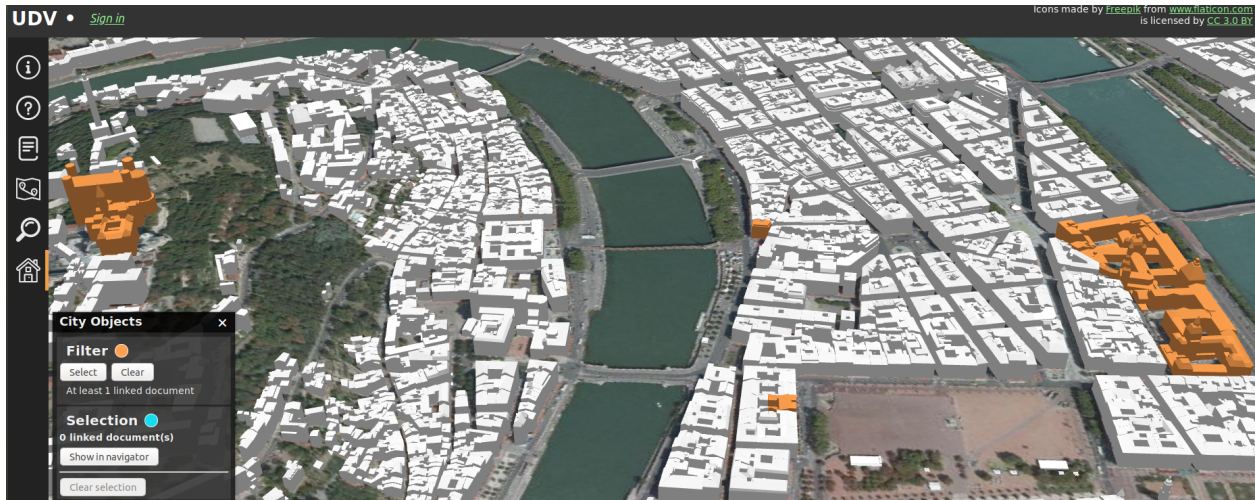


Figure 13: City objects filters example. City objects having at least one linked document are displayed in orange in the 3D scene.

In addition to these modes of navigation and access to information of multimedia documents and 3D city models, we also added the possibility to project documents in the 3D scene by displaying them in superimposition to the 3D model. This is particularly interesting for images and it allows integrating them in the 3D view (see figure 14). This visualization functionality complements the navigation possibilities offered by using links that is more generic because it is not limited to images that can be projected in a 3D scene (e.g. pictures). It is also possible to displace in a spatial context from a source point A to reach a target point B (with a parametric curve to link this flyover). A second functionality based on a possible storytelling process also allows the following of a trajectory in space and time.



Figure 14: Example of the projection of a document in the 3D scene.

We have also implemented participatory functionalities allowing users to add multimedia documents directly into the application after creating an account. These documents can also be validated by experts or moderators and users can leave comments attached to documents. These functionalities are useful to allow experts (e.g. historians, geographers, etc.) to add new knowledge in the application and to discuss this knowledge with other experts, with all the possibilities that the linking system we proposed allows in terms of navigation and exploration. In addition, it can also be particularly useful to open the possibility to add multimedia documents to non-experts such as citizens, tourists or associations members that have information to share or who are eager to discover the city. The users who submit the documents to the platform need to make a declaration of the ownership and the moderation process ensures that only the documents with appropriate public licences are shown on the application.

In this context, our tool has been tested by researchers and practitioners working in the field of cultural heritage: researchers in social sciences (in the fields of anthropology and geography with specific expertise on cultural heritage), the "cultural heritage and general inventory" department of the city of Lyon and of the *Auvergne-Rhône-Alpes* region (France). This usage led to the integration of some multimedia documents from their official database in our prototype and to the demonstration that (i) our prototype resulting from the research proposed in this article is usable and (ii) to propose prospective elements to this institution on how partnerships with research institutions and how such tools may be beneficial for them in their day to day work. In particular, this proposition interested researchers in the perspective of gathering data from non-experts to open a discussion about cities cultural heritage, its making and may be leading to the emergence of elements that could possibly be recognized as cultural heritage in the future. Practitioners recognized a potential for gathering and communicating about the city and its cultural heritage to a diverse audience going from colleagues to students.

We have paid particular attention to the **reproducibility** of the experiments realized in this article. First, we provide **permalinks to the specific versions of the code** allowing the reproduction of the experiments by using the Software Heritage archive¹⁵. Secondly, we provide **permalinks to the data used and produced** in this article by using Zenodo¹⁶. This guarantees durability of the data and source code. Thirdly, we provide detailed **installation scripts and notes** based on shell and Docker¹⁷

¹⁵<https://www.softwareheritage.org/>

¹⁶<https://zenodo.org/>

¹⁷<https://www.docker.com/>

to install and reproduce the results and the demonstrations presented in this article. The functionalities and results presented in this section can be reproduced¹⁸¹⁹

7 Conclusion

In this article, we proposed a two-step approach for integrating multimedia documents and time-evolving 3D city models for navigation and visualization on the web. First, we provided a generic conceptual model for linking **features** (**GenLinkable** model) in section 4.1. This model has the advantages to be generic to all features and of being non-intrusive in the features' models (i.e. it allows their linkage without the need to modify their individual data models). Secondly, we specified this model to integrate time-evolving 3D city models and multimedia documents (**Gen4DCity-Doc** model) in section 4.2. This model enhances *Gen4DCity* (proposed in a previous research article (Jaillot, Servigne, et al., 2020)) with multimedia documents and therefore allows pushing forward possibilities for cities representation, description and visualization. Thirdly, we proposed an implementation for 3D city objects and multimedia documents integration and navigation in a 4-tier web architecture based on open software and on open standards (section 5). Finally, we presented uses and results as well as a detailed online documentation to ensure reproducibility (section 6). In this last section, we have also shown that these tools can be useful for researchers and practitioners in the field of cultural heritage.

This work opens potentials for new research and developments. First, our generic proposition (*GenLinkable*) could be enhanced to permit linkage of subsets of features. For instance, let us consider a multimedia document that needs to be related to a fragment of a wall (e.g. for specifying renovation work to do on this fragment of wall). If the wall fragment is not defined as a feature in the city model, 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. Allowing the linking of feature subsets may be interesting in such cases to provide more flexibility. In order to provide a better way to search and filter documents in space and time, there is a need to extend the current limited capacity to navigate temporally in the 3D environment with a temporal slider. One interesting lead to do so may be to extend and specify the *Anchor* concept proposed in Papa et al. (1994). A more long-term goal opening up possibilities for new research and uses would be to specify *GenLinkable* for other type of features than multimedia documents and 3D city models. One identified use case (Chaturvedi & Kolbe, 2019) 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.) and 3D city models. Gathering and integrating these resources using *GenLinkable* would result in creating a shared model with many resources describing the city, based on standards and used for web visualization and navigation. This work also requires a much more detailed study and testing on user participation.

References

- Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., & Çöltekin, A. (2015). Applications of 3D city models: State of the art review. *ISPRS International Journal of Geo-Information*, 4(4), 2842–2889.
- Brivio, P., Benedetti, L., Tarini, M., Ponchio, F., Cignoni, P., & Scopigno, R. (2013). PhotoCloud: Interactive remote exploration of large 2d-3d datasets. *IEEE Computer Graphics and Applications*, 33, 86–96. <http://veg.isti.cnr.it/Publications/2013/BBTPCS13>
- Bruschke, J., & Wacker, M. (2016). Simplifying documentation of digital reconstruction processes. In S. Münster, M. Pfarr-Harfst, P. Kuroczyński, & M. Ioannides (Eds.), *3d research challenges in cultural heritage II* (pp. 256–271). Springer International Publishing.
- Busayarat, C. (2010). *La maquette numérique comme support pour la recherche visuelle d'informations patrimoniales: Définition d'une approche pour la sémantisation de sources iconographiques par référencement spatial*. (Doctoral dissertation). Arts et Métiers ParisTech. Retrieved August 22, 2017, from <https://hal.archives-ouvertes.fr/pastel-00557514/>

¹⁸<https://archive.softwareheritage.org/swh:1:dir:247366dc021f2b61a3d8abf6bc07be35b4e5d734;origin=https://github.com/VCityTeam/UD-Reproducibility/>

¹⁹The 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.

- Busayarat, C., De Luca, L., Veron, P., & Florenzano, M. (2010). Semantic annotation of heritage building photos based on 3d spatial referencing. *Proceedings of Focus K3D conference on Semantic 3D Media and Content*.
- Chagnaud, C., Samuel, J., Servigne, S., & Gesquière, G. (2016). Visualization of documented 3d cities. *Eurographics Workshop on Urban Data Modelling and Visualisation, Liège, Belgium*.
- Chaturvedi, K., & Kolbe, T. H. (2019). A requirement analysis on extending semantic 3D city models for supporting time-dependant properties. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, IV-4/W9*, 19–26. <https://doi.org/10.5194/isprs-annals-IV-4-W9-19-2019>
- Chaturvedi, K., Smyth, C. S., Gesquière, G., Kutzner, T., & Kolbe, T. H. (2017). Managing versions and history within semantic 3d city models for the next generation of CityGML. *Advances in 3d Geoinformation* (pp. 191–206). Springer. Retrieved August 21, 2017, from http://link.springer.com/chapter/10.1007/978-3-319-25691-7_11
- De Luca, L. (2014). Methods, formalisms and tools for the semantic-based surveying and representation of architectural heritage. *Applied Geomatics*, 6(2), 115–139. <https://doi.org/10.1007/s12518-011-0076-7>
- De Luca, L., Busayarat, C., Stefani, C., Véron, P., & Florenzano, M. (2011). A semantic-based platform for the digital analysis of architectural heritage. *Computers & Graphics*, 35(2), 227–241.
- Dewitz, L., Kröber, C., Messemer, H., Maiwald, F., Münster, S., Brusckke, J., & Niebling, F. (2019). Historical photos and visualizations: Potential for research. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2-W15*, 405–412. <https://doi.org/https://doi.org/10.5194/isprs-archives-XLII-2-W15-405-2019>
- Dublin Core Metadata Initiative. (2012). *DCMI Metadata Terms* (Standard). Retrieved November 26, 2019, from <https://www.dublincore.org/specifications/dublin-core/dcmi-terms/>
- Hervy, B., Billen, R., Laroche, F., Carré, C., Servièrès, M., Van Ruymbeke, M., Tourre, V., Delfosse, V., & Kerouanton, J.-L. (2012). A generalized approach for historical mock-up acquisition and data modelling: Towards historically enriched 3d city models. In T. Leduc, G. Moreau, & R. Billen (Eds.), *Usage, Usability, and Utility of 3d City Models – European COST Action TU0801* (p. 02009). EDP Sciences. <https://doi.org/10.1051/3u3d/201202009>
- International Organization for Standardization. (2008). *Geographic information - Terminology* (Standard ISO 19104:2008). Retrieved January 20, 2020, from <https://www.iso.org/standard/63541.html>
- Jaillot, V., Istasse, M., Servigne, S., Gesquière, G., Rautenberg, M., & Lefort, I. (2020). Describing, comparing and analysing digital urban heritage tools: A methodology designed with a multidisciplinary approach. *Digital Applications in Archaeology and Cultural Heritage*, 17, e00135. <https://doi.org/10.1016/j.daach.2020.e00135>
- Jaillot, V., Pedrinis, F., Servigne, S., & Gesquière, G. (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*, 10–pages.
- Jaillot, V., Servigne, S., & Gesquière, G. (2020). Delivering time-evolving 3D city models for web visualization. *International Journal of Geographical Information Science*.
- Kolbe, T. H. (2009). Representing and Exchanging 3d City Models with CityGML. In J. Lee & S. Zlatanova (Eds.), *3d Geo-Information Sciences* (pp. 15–31). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-87395-2_2
- Laroche, F., Alain, B., & Hervy, B. (2015). DHRM: A new model for PLM dedicated to product design heritage. *CIRP Annals - Manufacturing Technology*, 64, 4p. <https://doi.org/10.1016/j.cirp.2015.04.027>
- Ledoux, H., Arroyo Ogori, K., Kumar, K., Dukai, B., Labetski, A., & Vitalis, S. (2019). CityJSON: A compact and easy-to-use encoding of the CityGML data model. *Open Geospatial Data, Software and Standards*, 4(1), 4. <https://doi.org/10.1186/s40965-019-0064-0>

- Maiwald, F., Bruschke, J., Lehmann, C., & Niebling, F. (2019). A 4d information system for the exploration of multitemporal images and maps using photogrammetry, web technologies and VR/AR. *Virtual Archaeology Review*, 10(21), 1. <https://doi.org/10.4995/var.2019.11867>
- Manuel, A. (2016). *Annotation sémantique 2D/3D d'images spatialisées pour la documentation et l'analyse d'objets patrimoniaux* (Doctoral dissertation). Ecole nationale supérieure d'arts et métiers-ENSAM. Retrieved August 22, 2017, from <https://pastel.archives-ouvertes.fr/tel-01304776/>
- Métral, C., Falquet, G., & Vonlanthen, M. (2007). An ontology-based model for urban planning communication. In J. Teller, J. R. Lee, & C. Roussey (Eds.), *Ontologies for urban development* (pp. 61–72). Springer. https://doi.org/10.1007/978-3-540-71976-2_6
- Meyer, E., Grussenmeyer, P., Perrin, J.-P., Durand, A., & Drap, P. (2007). A web information system for the management and the dissemination of Cultural Heritage data. *Journal of Cultural Heritage*, 8(4), 396–411.
- Münster, S., Niebling, F., Bruschke, J., Barthel, K., Friedrichs, K., Kröber, C., & Maiwald, F. (2020). Urban History Research and Discovery in the Age of Digital Repositories. A Report About Users and Requirements. In H. Kremers (Ed.), *Digital Cultural Heritage* (pp. 63–84). Springer International Publishing. https://doi.org/10.1007/978-3-030-15200-0_5
- Nakaya, T., Yano, K., Isoda, Y., Kawasumi, T., Takase, Y., Kirimura, T., Tsukamoto, A., Matsumoto, A., Seto, T., & Iizuka, T. (2010). Virtual Kyoto Project: Digital Diorama of the Past, Present, and Future of the Historical City of Kyoto. In T. Ishida (Ed.), *Culture and Computing: Computing and Communication for Crosscultural Interaction* (pp. 173–187). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-17184-0_14
- Open Geospatial Consortium. (2012). *OGC City Geography Markup Language (CityGML) Encoding Standard 2.0.0* (Standard OGC 12-019). Retrieved November 25, 2019, from <http://www.opengis.net/spec/citygml/2.0>
- Open Geospatial Consortium. (2017). *OGC Indexed 3d Scene Layer (I3S) and Scene Layer Package Format Specification v1.0* (Standard 17-014r5). Retrieved September 30, 2019, from <https://docs.opengeospatial.org/cs/17-014r5/17-014r5.html>
- Open Geospatial Consortium. (2019). *OGC 3d Tiles Specification 1.0* (Standard 18-053r2). Retrieved December 12, 2019, from <http://docs.opengeospatial.org/cs/18-053r2/18-053r2.html>
- Pamart, A., Morlet, F., & de Luca, L. (2019). A fully automated incremental photogrammetric processing dedicated for collaborative remote-computing workflow. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W9*, 565–571. <https://doi.org/10.5194/isprs-archives-XLII-2-W9-565-2019>
- Papa, M. P., Ragucci, G., Corrente, G., Ferrise, M., Giurleo, S., & Vitale, D. (1994). The development of an object-oriented multimedia information system. In E. Bertino & S. Urban (Eds.), *Object-oriented methodologies and systems* (pp. 278–297). Springer Berlin Heidelberg.
- Pédrinis, F., Morel, M., & Gesquière, G. (2015). Change detection of cities. *3D geoinformation science* (pp. 123–139). Springer. Retrieved August 21, 2017, from http://link.springer.com/chapter/10.1007/978-3-319-12181-9_8
- Pfeiffer, M., Carré, C., Delfosse, V., Hallot, P., & Billen, R. (2013). Virtual Leodium: From an historical 3D city scale model to an archaeological information system. *ISPRS Annals—Volume II-5/W1, 2013*. Retrieved August 21, 2017, from <http://orbi.ulg.ac.be/bitstream/2268/157663/1/CIPA2013-108-1.pdf>
- Renolen, A. (2000). Modelling the Real World: Conceptual Modelling in Spatiotemporal Information System Design. *Transactions in GIS*, 4(1), 23–42. <https://doi.org/10.1111/1467-9671.00036>
- Robinson, A. C. (2011). Highlighting in Geovisualization. *Cartography and Geographic Information Science*, 38(4), 373–383. <https://doi.org/10.1559/15230406384373>

- Samuel, J., Servigne, S., & Gesquière, G. (2018). UrbanCo2Fab: Comprehension of concurrent viewpoints of urban fabric based on git. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, IV-4/W6*, 65–72. <https://doi.org/10.5194/isprs-annals-IV-4-W6-65-2018>
- Samuel, J., Périnaud, C., Servigne, S., Gay, G., & Gesquière, G. (2016). Representation and Visualization of Urban Fabric Through Historical Documents [event-place: Genova, Italy]. *Proceedings of the 14th Eurographics Workshop on Graphics and Cultural Heritage*, 157–166. <https://doi.org/10.2312/gch.20161399>
- Samuel, J., Servigne, S., & Gesquière, G. (2020). Representation of concurrent points of view of urban changes for city models. *Journal of Geographical Systems*. <https://doi.org/10.1007/s10109-020-00319-1>
- Schindler, G., & Dellaert, F. (2012). 4d Cities: Analyzing, Visualizing, and Interacting with Historical Urban Photo Collections. *Journal of Multimedia*, 7(2). <https://doi.org/10.4304/jmm.7.2.124-131>
- Siabato, W., Claramunt, C., Ilarri, S., & Manso-Callejo, M. A. (2018). A Survey of Modelling Trends in Temporal GIS. *ACM Comput. Surv.*, 51(2), 30:1–30:41. <https://doi.org/10.1145/3141772>
- Snavely, N., Seitz, S. M., & Szeliski, R. (2006). Photo Tourism: Exploring Photo Collections in 3d [event-place: Boston, Massachusetts]. *ACM SIGGRAPH 2006 Papers*, 835–846. <https://doi.org/10.1145/1179352.1141964>
- Stefani, C., De Luca, L., Véron, P., & Florenzano, M. (2010). Time indeterminacy and spatio-temporal building transformations: An approach for architectural heritage understanding. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 4(1), 61–74.
- Tardy, C., Mocozet, L., & Falquet, G. (2012). Semantic alignment of documents with 3d city models. In T. Leduc, G. Moreau, & R. Billen (Eds.), *Usage, usability, and utility of 3d city models – european COST action TU0801* (p. 02011). EDP Sciences. <https://doi.org/10.1051/3u3d/201202011>
- Trapp, M. (2013). *Interactive rendering techniques for focus+ context visualization of 3d geovirtual environments* (PhD Thesis). Universitätsbibliothek der Universität Potsdam.
- Weibel, S. (1997). The Dublin Core: A Simple Content Description Model for Electronic Resources. *Bulletin of the American Society for Information Science and Technology*, 24(1), 9–11. <https://doi.org/10.1002/bult.70>