



HAL
open science

UD-SV : Urban data services and visualization framework for sharing multidisciplinary research

John Samuel Samuel, Vincent Jaillot, Clément Colin, Diego Vinasco-Alvarez,
Eric Boix, Sylvie Servigne, Gilles Gesquière

► **To cite this version:**

John Samuel Samuel, Vincent Jaillot, Clément Colin, Diego Vinasco-Alvarez, Eric Boix, et al.. UD-SV : Urban data services and visualization framework for sharing multidisciplinary research. Transactions in GIS, 2023, 27 (3), pp.841-858. 10.1111/tgis.13049 . hal-04071150

HAL Id: hal-04071150

<https://hal.science/hal-04071150v1>

Submitted on 8 Jun 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

UD-SV: Urban Data Services and Visualization Framework for Sharing Multidisciplinary Research

John Samuel¹, Vincent Jaillot², Clément Colin^{3,5}, Diego Vinasco Alvarez², Eric Boix⁴, Sylvie Servigne⁴, and Gilles Gesquière²

¹CPE Lyon, LIRIS, UMR-CNRS 5205, Université de Lyon, Lyon, France

²Université Lumière Lyon 2, LIRIS UMR-CNRS 5205, Université de Lyon, Lyon, France

³Université de Lyon, LIRIS UMR-CNRS 5205, France

⁴INSA Lyon, LIRIS UMR-CNRS 5205, Université de Lyon, Lyon, France

⁵Carl Software, Limonest, France

March 7, 2023

Abstract

With the widespread availability of a large volume of urban data, stakeholders from different domains require advanced tools to manage, visualize and understand cities and their evolution. During the last few years, researchers have proposed numerous research works and applications to illustrate the cities of the past and possible scenarios of the future under different conditions. However, many of these approaches are one-time solutions and not based on standards, making them obsolete and unusable for reproducible research. In this article, we present *UD-SV: an Urban data-Services and Visualization*, an open-source framework for multidisciplinary research to handle complex processing, analysis, and visualization of urban data. However, our goal is not to present a one-time monolithic software solution for urban data management and analysis, but we demonstrate the design and development of an open and interoperable software framework driven by use cases from diverse users to solve applied research challenges. The main contribution of UD-SV is that it uses open standards and open

data with documented and reproducible processes with a particular emphasis on the reuse of existing open-source software components. We also show an enhanced use of standards to enable a shift towards components that are interchangeable or composable with other existing components in the GIS community.

1 Introduction

Common ways to visualize cities include 2D maps in print or online devices, usually showing the footprint of city objects like buildings. 3D visualization, on the other hand, helps the user visualize city object structures. Adding a temporal dimension to this 3D visualization often involves letting the user navigate the structural changes to cities at different scales and at different time periods. As such, 4D navigation is becoming a new way to discover and query cities. Moreover, users now wish to easily manage, enhance and share information concerning a given area, whether for their personal usage or a community such as in OpenStreetMap [OpenStreetMap].

Using these recent advances in 3D and 4D visualizations, urban digital twins [Dembski et al., 2020] show digital representations of cities composed of heterogeneous, multi-source, and multidimensional data like cadastral information, information on vegetation, city networks, water bodies, or any other information and knowledge that can help represent and describe cities. They are constructed as the 3D digital equivalent of cities in a manner that allows the users to navigate these virtual environments horizontally and vertically as though they are in the real world [Nakaya et al., 2010, Kaplan, 2015]. We can also define urban digital twins by a set of features that are an “abstraction of real-world phenomena” according to the ISO (International Organization for Standardization) [International Orga-

nization for Standardization, 2008] and the OGC (Open Geospatial Consortium) [OGC, b]. Features define 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 is described with geometric objects (e.g. points, polylines, polygons, or volumes) located in a coordinate reference system (2D or 3D). A feature can also have a temporal dimension to describe its diachronic nature with timestamps, time intervals, etc. A feature can also be self-composed and enriched with thematic information.

Other kinds of data like multimedia corpus (photographs, municipal records, old postal cards, newspaper articles, videos, etc.) are also available and often used independently from the prior ones. Additionally, participatory approaches encourage citizens to share and contribute old album photographs, and newspapers, further enriching the document corpus. Researchers such as historians or geographers may benefit from the integration of this multimedia corpus in urban digital twins. Furthermore, navigation in this multimedia corpus may be enhanced by this integration, creating relations with city objects, and allowing further urban analyses. Including all these data constitutes a large volume of urban data, typically running into hundreds of gigabytes, even for a single district of a city¹.

Traditionally, geographical information systems (GIS) helped users in the analysis and visualization of 2D urban information. GIS is well-defined and numerous tools and components are already existing. However, GIS requires some necessary evolution such as the linking of temporal, 3D, and multimedia information with the usual data. This means progressively shifting towards covering a much broader scope, whether on the aspect of data, by involving complex digital twins composed

¹<https://data.grandlyon.com/>

of heterogeneous, and multidimensional data sets, or on the functionalities covered and types of users addressed. Therefore, GIS research and industry require data, methods, and modular tools that can be easily integrated, reproduced, and shared. Furthermore, organizing urban data in an interoperable context is essential. For example, we can cite CityGML OGC Standard [OGC, a] that fills an important gap by providing 3D data models and by tackling interoperability challenges.

A careful study of the needs of the GIS community (with focus on heritage data) and the study of several dozens of available tools and applications [Jaillot et al., 2020a] allowed us to identify some of the requirements for a modern nD (3D, temporal, thematic) framework for digital twins (Figure 1). Unfortunately, a majority of these applications lacked the possibility to reuse components and replicate or reproduce these works. Moreover, the use of GIS is increasingly becoming multidisciplinary with discussions involving city administrations, companies, computer science researchers, practitioners, historians, urban planners, etc. Towards this direction, we propose and develop a framework for building reproducible and reusable services: UD-SV (Urban Data Services and Visualization) to address these problems. We describe their implementation in an extensible platform for urban web applications based on a 4D city data browser. Our proposed solution, UD-SV serves the purpose of providing and gathering tools for urban digital twins to test and explore new research propositions by diverse multidisciplinary researchers. It is based on a 4-tiers architecture and is developed according to the following principles: modularity, reusability, interoperability, and reproducibility. In our context of work (public research lab), the development cycle is short and driven by the evolving requirements of the GIS community. We have chosen an agile approach with successive iterations based on community feedback by demonstrating what is

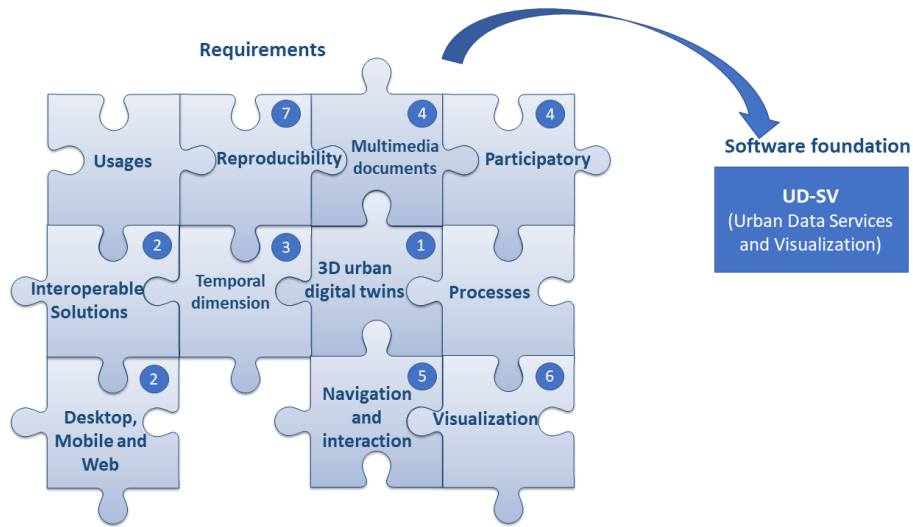


Figure 1: Software framework requirements for UD-SV. Driven by use cases, UD-SV supports multiple computation processes responding to the seven major requirements. The conception of the solutions to these requirements constitute the software foundation of UD-SV.

currently possible and discussing it with the community for further improvements.

We identified the key requirements highlighted in Figure 1 which also gives a global view of UD-SV. Solutions to all the requirements (R) are available in UD-SV. UD-SV demonstrates the use-case-driven context of the GIS, built on interoperable solutions (R2) for 3D urban digital twins (R1) available on desktop or mobile devices and the web (R2). It also incorporates the temporal dimension (R3) for managing the evolving urban landscape, augmented with multimedia documents (R4) and information obtained from participatory approaches (R4). Furthermore, users can interact and navigate (R5) urban digital twin created using UD-SV components and are able to visualize (R6) the city in different ways. Finally, our proposed solution is also reproducible (R7). These requirements could be used for building different (computational) processes for multidisciplinary usages. Figure 1 also shows the role of computation processes for different usages. In UD-SV, R1

is enriched with R3 and R4 in an R2 environment to ensure R5, R6 as well as R7.

Our main research question is how to access, manage, navigate, and visualize an nD urban environment in an open, interoperable, and reproducible approach. Compared to traditional monolithic applications, our goal is to provide a modular framework, where new computational processes for evolving urban analysis needs can be easily integrated or removed. Our main contributions proposed in this article are the following:

- description of the design and development of an **operational and open-source framework** for urban data analysis and visualization with the capacity to mobilize data, particularly for visualizing the city and its evolution.
- description of a **process** for creating a solid foundation to support research beyond publications with reproducible code that does not fall into oblivion at the end of the project.
- illustration of the design and development of **atomic components**:
 - that can be composed for applications in a given use case.
 - that can be easily mixed with already available (external) components.
 - that can be used by non-specialists.
 - that are reproducible and reusable.
- description of the design and development of **urban data services** for multidisciplinary research.
- demonstration of short development cycles while allowing longer-term maintenance for applications (for example, py3DTiles and iTowns).

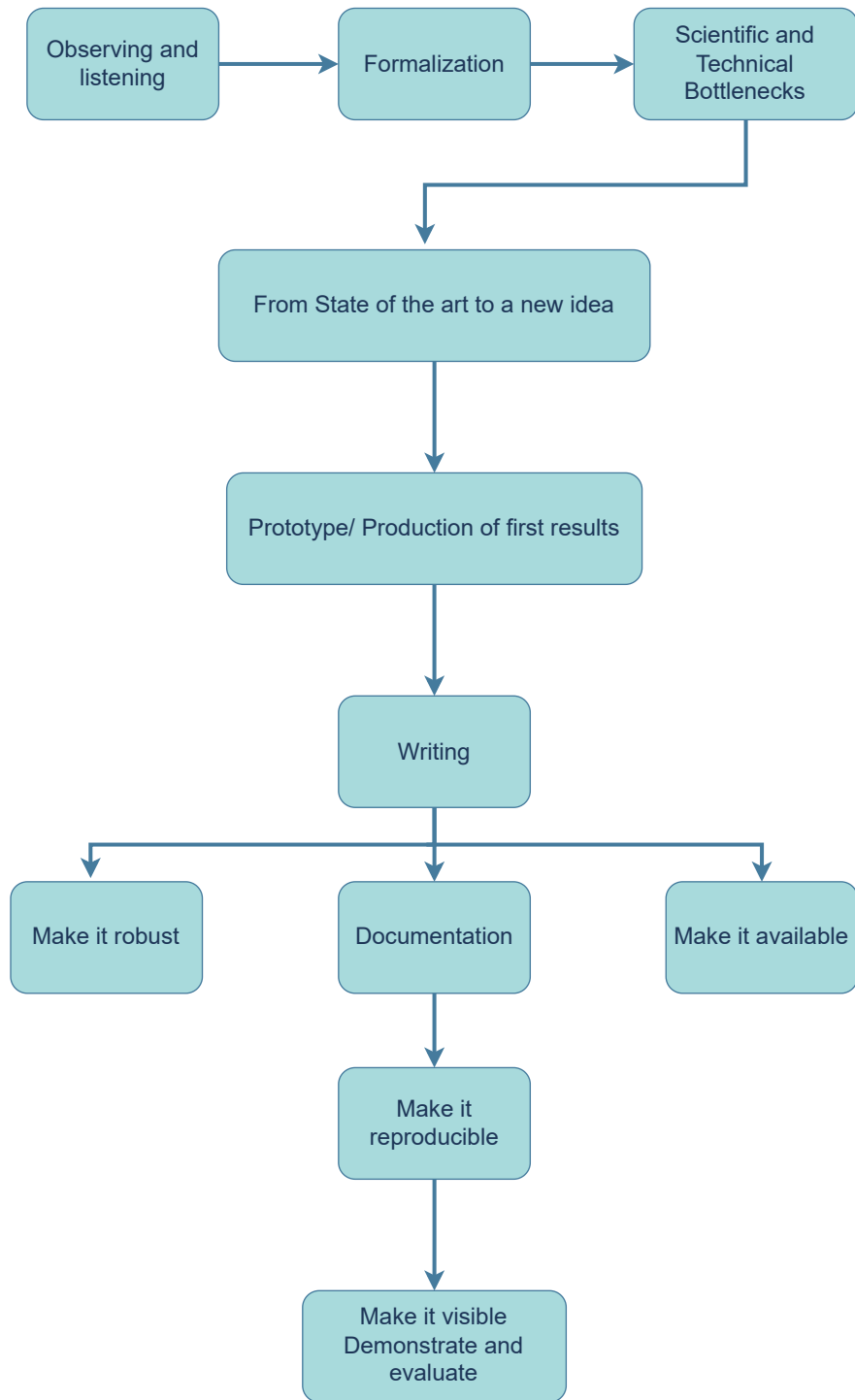


Figure 2: Desired Methodology in UD-SV. It demonstrates the major steps from identifying the requirements and formalization of the problem to building a robust, documented, and reproducible solution.

In order to create the UD-SV framework we utilise the methodology illustrated in Figure 2. This methodology begins with observing and listening to multidisciplinary community members and project stakeholders across domains of research and industry to better understand what technologies and processes are being used in different use-cases of urban data research. Taking these observations into account we design functional and technical specifications, data models, and data pipelines to formalize how a specific problem can be described and solved. These formalized problems must be analyzed to determine what challenges such as scientific and technical bottlenecks must be overcome to solve the problem. Next, the state of the art is taken into consideration to identify what solutions already exist for tackling these challenges, which may require modifying the formalization to take into consideration these works. We may also discover that existing solutions to a scientific or technical challenge do not exist or are insufficient. Taking a modular approach, different existing works from potentially different domains or research and industry can be composed along with the development of new components when necessary to create prototypes or initial results. Finally these results along with the process towards their creation or development can be published as new research. Following a publication there are several tasks important for adding value to the algorithms and applications used to produce the results. In the context of multidisciplinary research, this means the code or application should be robust (scalable and usable for different urban datasets), well-documented, and publicly available. The documentation should include steps to build the application and/or reproduce the published results. Finally, once the documentation has reached a minimum level of maturity, it should be made public alongside potential demonstrations and possible evaluations with other existing solutions.

We present the computational methods, analyses and software components designed for UD-SV. Section 2 presents computational processes to prepare the information required for visualizing urban digital twins. Section 3 presents the architecture, the implementation, and examples of possible applications of UD-SV, reproducibility aspects and future course of actions. Some screenshots are also provided in this section. Finally, section 4 concludes our work.

2 Urban digital twin: computation processes and usages

In this section, we look at some of the existing works related to the requirements identified in Figure 1, discuss their limitations, and compare it with UD-SV. Table 1 gives an overview of works related to the computation processes and usages in urban digital twins as well as their limitations. We will also discuss how UD-SV handles some of these limitations. Our proposed framework is described in detail in section 3. As discussed above, UD-SV needs to respond to all the requirements and handle the evolving urban needs in a multidisciplinary context. We want to build a framework that supports management and visualization of nD urban cities based on standards. The framework must be interoperable and we want the ability to reuse existing standards and open-source software components.

In the past, a significant amount of tools and works focused on using 2D approaches for urban planning and historical studies. However, traditional 2D approaches can be limited in representing and visualizing evolving urban landscapes compared to 3D or 4D approaches [De Roo et al., 2013]. Works like Rizvic et al.

Computational processes	Works	Major Limitations
2.1. Interoperable solutions for desktop, mobile and web platforms	[Kolbe et al., 2005], [De Roo et al., 2013], [Gröger and Plümer, 2012], [Kutzner et al., 2020], [Gesquière and Manin, 2012], [Zhang et al., 2014], [Miao et al., 2017], [Münster et al., 2020], [Stefani et al., 2013]	<ul style="list-style-type: none"> • Missing use of standards • Evolving 3D web standards • Monolithic solutions
2.2. Temporal urban models	[Nakaya et al., 2010], [Pfeiffer et al., 2013], [De Roo et al., 2013], [Evans et al., 2006], [Kaplan, 2015], [Chaturvedi et al., 2017], [Samuel et al., 2020]	<ul style="list-style-type: none"> • Standards require extensions for time-dependant properties.
2.3. Navigation, interaction and visualization	[Köninger and Bartel, 1998], [Shiode, 2000], [Nurminen and Oulasvirta, 2008], [Zhang et al., 2014], [Shiode, 2000], [Zhou et al., 2006]	<ul style="list-style-type: none"> • Non-availability of (open)-data for realistic impression • Technological challenges for large-scale visualization of cities
2.4. Multimedia documents and user participation	[Snavely et al., 2006], [Schindler and Dellaert, 2012], [Chagnaud et al., 2016], [Pacheco et al., 2014], [Friedrichs et al., 2018], [Münster et al., 2020], [Chagnaud et al., 2016]	<ul style="list-style-type: none"> • Visualizing multimedia documents in 3D environments • Missing links between multimedia documents and city objects

Table 1: Computational Processes and Usages in Urban Digital Twins

[2015], Pfeiffer et al. [2013], De Roo et al. [2013], Nakaya et al. [2010], Beil and Kolbe [2017] proposed building digital twins focusing on a particular zone, sector of a given city or even a complete city. These approaches aimed to give a detailed picture of the chosen area like the objects of interest and their relationship with the surrounding environment like the terrain and the vegetation. Though these one-time solutions have provided insights to historians and researchers in the past, it is not possible to access and reproduce them. Because of the missing methodology and code, it is also difficult to apply and extend these solutions with new data from the same zone or data from other zones.

2.1 Interoperable solutions for desktop, mobile and web platforms

Several works [Kolbe et al., 2005, De Roo et al., 2013] propose conceptual data models with the possibility of querying, data exchange, data interoperability, by making use of international standards and by linking urban data to existing data sets. Cities have started using international standards like CityGML [Gröger and Plümer, 2012, Kutzner et al., 2020] and IFC (Industry Foundation Classes) [Smith, 2014] for representing 3D structures of city objects, detailed buildings and their associated semantic and thematic information. A major advantage is that the data released using these standards are interoperable and therefore not tied to any particular software application and therefore can be easily shared.

Recent years have seen many web-based platforms like Gesquière and Manin [2012], Zhang et al. [2014], Miao et al. [2017], Münster et al. [2020], Stefani et al. [2013] proposed for various types of urban analyses. However, developing and

managing a 3D geospatial information system on the web is challenging [Pispidikis and Dimopoulou, 2016]. Many of the above propositions for 3D web experience are very recent and hence still evolving. In addition, open standard specifications like 3DTiles are still at the technical specification level and these standards have not been completely implemented. Also, in order to integrate these standards, there is a need for a generic (and so more abstract) approach. A conceptual model [Jaillot et al., 2020b, Jaillot, 2020] of these standards and an implementation have been previously proposed to overcome these challenges. Such a conceptualization with a generic approach enhances effective interoperability among different 3D or nD city models.

We often find monolithic proposals in most of the above works. It is important to be able to propose components that can be aggregated and thus reused in a particular framework. UD-SV proposes the use of components like 3DCityDB or even Geoserver which are easily usable thanks to the use of standards in these components.

2.2 Temporal urban models

Cities also change and have stories to tell of their past. Efforts like Virtual Kyoto project [Nakaya et al., 2010], Virtual Leodium [Pfeiffer et al., 2013, De Roo et al., 2013], Virtual London [Evans et al., 2006] have been proposed and are being developed during the last decades with the goal of providing users a virtual environment based on urban digital twins for understanding historical changes. The users of these projects can not only view the historical buildings at a given time but also visualize the changes that occurred to these buildings in a given period of time.

We can classify these proposals into two. The first set of proposals is dedicated to urban evolution (for instance, the evolution of Kyoto during time). In the second set, we sometimes see a storytelling approach with these applications and the second set of applications is based on archives (especially, textual documents) that can be managed in time and space (for example, Venice time machine [Kaplan, 2015]). We aim to support the two types of proposals simultaneously.

Some of the above standards like CityGML need to be extended to represent information related to urban evolution. Chaturvedi and Kolbe [2019], for example, gives an overview of the different ways by which the 3D CityGML model has been extended with time-dependent properties. Chaturvedi et al. [2017] propose ways to represent various versions of urban heritage [Samuel et al., 2020]. These use cases of UD-SV were studied during the ALARIC² project [Samuel et al., 2016] which helped us to understand the needs of urban planners and historians for studying and representing the incremental urban changes for understanding and projecting the evolving urban landscape. These extensions are present in CityGML 3.0 (Kutzner et al. [2020]). However, to the best of our knowledge, the implementations of these extensions in a generic approach at the city scale are not currently available. UD-SV has integrated the recent proposal of creating temporal tilesets [Jaillot, 2020] that is capable of improving the quality problems of real-world urban data, detecting geometric and semantic changes between two different vintages and aggregating these vintages in a time-evolving 3D city model.

2.3 Navigation, interaction and visualization

A generic approach to navigation and integration in urban digital twin requires

²<https://projet.liris.cnrs.fr/vcity/partnerprojects/alaric-project/>

a proper understanding of the several possible usages by different categories of users: historians, researchers, tourists, etc. Such an approach also requires an understanding of existing applications for building an abstract model. 3D urban modeling and visualization (Königer and Bartel [1998], Shiode [2000], Nurminen and Oulasvirta [2008], Zhang et al. [2014]) not only gives a view of the horizontal expanse of the cities but also their vertical expansion. The users obtain information about the height of different city objects, especially the buildings, and compare two or more objects. Many approaches have been made to visualize 3D urban city models [Shiode, 2000] and a balance has been made between the amount of reality, application performance in rendering the city objects, and functions. Hence, we can see approaches where building structures are mapped with their image-based texture [Zhou et al., 2006] giving quasi-total realistic information. CAD (Constructed Aided Design) based models may also give an almost realistic impression, but such detailed models are difficult to visualize for large-scale visualization of cities, because of current technical limitations [Gaillard et al., 2020]. To build a generic and open urban digital twin, UD-SV ensures the possibility of sharing urban data and interoperability of standards. The components are not tightly coupled, which ensures the possibility to easily change different components, like the client or the server side with very little programming effort. With its use of standards like CityGML and BIM-IFC, UD-SV is able to visualize different details of information at different scales: textures for large-scale visualizations and materials present in a room at the building interior level.

2.4 Multimedia documents and user participation

The next possible extension is for representing the information stored in multimedia documents concerning urban evolution. Many research works propose different visualization approaches for historical photographs [Snavely et al., 2006, Schindler and Dellaert, 2012, Chagnaud et al., 2016, Pacheco et al., 2014]. Friedrichs et al. [2018], Münster et al. [2020] analyzed usages of the digital corpus of photographs by art and archaeological historians and proposes a 4D web environment with a goal to improve the search and retrieval of digital documents in the 4D environment. This environment allows the users to not only view 3D structures of buildings along with the associated photographs, preserving their orientation but also allows the users to navigate the historical timeline. Dewitz et al. [2019] also used 4D virtual city models to study the most photographed buildings using heatmaps and were also capable of demonstrating different photographs at different times. Maiwald et al. [2019] proposed multimodal access strategies on large image corpus. Schindler and Dellaert [2012] proposed 4D virtual city models, historical photographs superposed over 3D city models giving users a way to see how the historical photographs have been taken. Snavely et al. [2006] also proposed a system for browsing images and for answering questions like which images depicted a particular scene or which photographs were taken close to a given image. Pacheco et al. [2014] proposed augmented reality, 3D reconstruction and visualization to allow human data interaction with cultural heritage objects using mobile devices. The approach followed in UD-SV for document integration is an extension of the functionalities proposed by Chagnaud et al. [2016] that used a desktop-based solution called 3DUSE and proposed a billboard-based display for visualizing historical documents. With the

participatory approach in UD-SV, users can also manually specify the link between the multimedia documents and the associated city objects.

3 UD-SV: An extensible framework based on a service oriented architecture

We now present the software and technical architecture of UD-SV, the overview of components, a practical demonstration, reproducibility aspects, limitations of the framework, and future works.

3.1 Software and technical architecture

We designed and implemented UD-SV (Urban Data Services and Visualization) as 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-tiers architecture and is composed of components developed by our team and other external components (including some of which we contribute to). Such multi-tier architecture [Albayati et al., 2021, Lei et al., 2022] helps to ensure modularity and creation of dedicated components for data management, computation or analysis, presentation, server, and clients. The 4-tiers software and technical architecture of UD-SV are presented in Figure 3. The four tiers are the client tier, web server tier, processing server tier, and data tier. The client tier consisting of UD-Viz (developed using iTowns) is used for the urban data visualization on the web using web browsers. The web server tier handles the client requests and loads the relevant tiles and information. The processing tier prepares the 3D tiles and performs various geospatial processes.

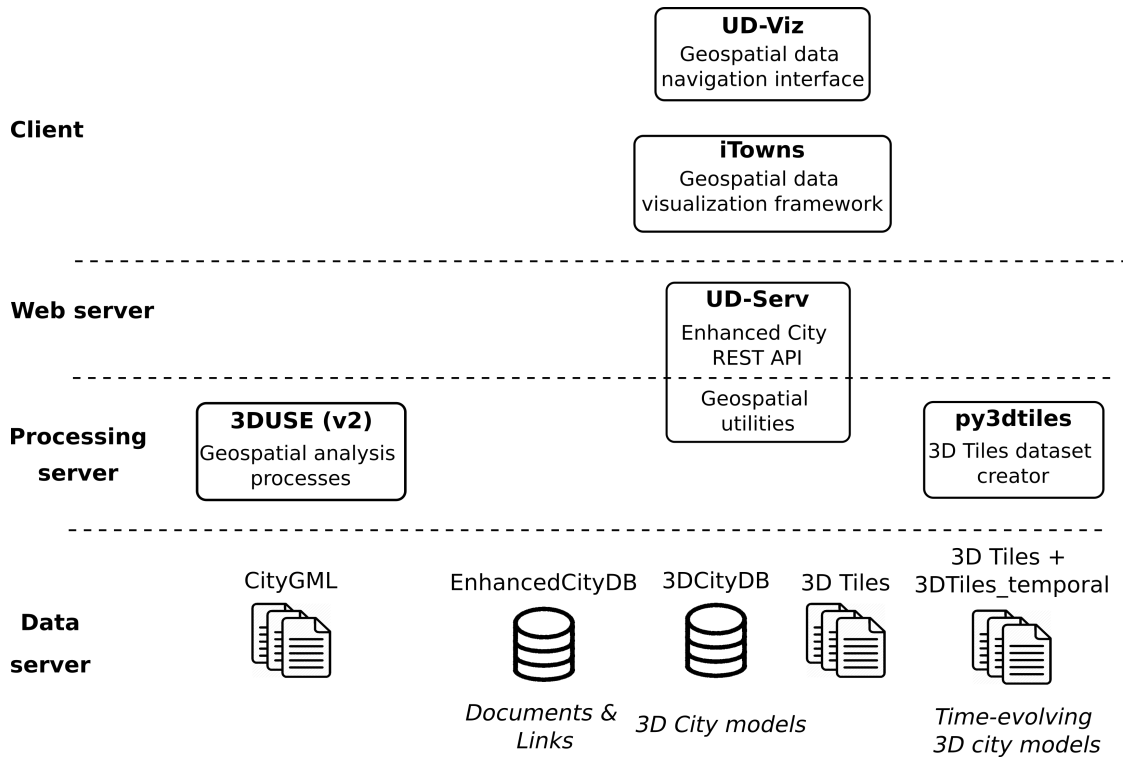


Figure 3: Software and 4-tier technical architecture of UD-SV. Four tiers: client, web server, processing server, and data server. The client and web server together constitute the client-server web architecture style allowing users to access UD-SV on web browsers. Data server tier stores and manages the different types of urban data formats. The processing server tier performs the necessary computations for enabling visualization.

The data tier consists of unprocessed CityGML files, 3DCityDB, and the processed 3DTiles (with temporal information) obtained from the processing tier. The web server tier can load data from processed files and the 3DCityDB database. Only 3DUSE (v2) can directly work with CityGML files.

The data server tier: The *data server tier* contains 3D city models represented in three different ways: as files in the CityGML format or 3D Tiles format and in a *3DCityDB* database. Some UD-SV processes (and those in 3DUSE, the desktop

version before UD-SV), use CityGML files as input, while other processes (e.g. from Py3DTiles) use a *3DCityDB* database. The 3D Tiles format is used for visualization in UD-Viz. The *data server tier* is also composed of time-evolving 3D city models stored as 3D Tiles with the *3DTiles_temporal* extension.

The processing server tier: The *processing server tier* contains 3DUSE, *py3DTiles* and geospatial utilities of UD-SV that implement geospatial data processes and provide a GUI for visualizing geospatial data (e.g. 3D city models in the CityGML format, shapefiles, etc.). Py3DTiles is developed and maintained by Oslandia [Oslandia] and converts geospatial data from various data formats (e.g. CityGML, LAS) or from a 3DCityDB database into 3D Tiles datasets. We contribute to the development of this software component with engineering and implementation of research propositions. Finally, utilities of *UD-Serv* consists of processes like *CityGML2Stripper* which strips a CityGML 2.0 file of its appearance and generic attributes and serializes the result back into a new CityGML file.

The web server tier: The *web server tier* 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 realizing *CRUD* (Create, Read, Update, Delete) operations on the multimedia documents, links, contributors, comments, etc. *UD-Serv* is programmed in Python.

The client tier: The end-user application located on *the client tier* is *UD-Viz*, written in JavaScript and based on several libraries, especially *iTowns*. *UD-Viz* manages the interface, multimedia documents and links, users and some useful modules such as address search. *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 in turn based on WebGL and ThreeJS and is mainly developed and maintained by the IGN [IGN] (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.

3.2 Overview of Current Services and Components

Users coming to UD-SV may see a 3D representation of an urban area. They can navigate around the digital twin, performing operations like zooming and panning. They can click on any object of interest and see the available information related to the object. They can navigate the virtual city as though they are in a real one but at a reduced scale. Hence, they can compare the height of city objects like buildings and the visibility of objects from a particular point of view. They may also make use of a temporal cursor to navigate the different snapshots of the city. Sometimes, users may wish to explore a specific zone or an address. Other miscellaneous functionalities include geocoding, positioning of cameras or obtaining the position of an object or a point of interest in the urban digital twin. These additional features ensure that other users with whom these values were shared can reproduce a 3D scene of interest.

Temporal navigation and Multimedia sources: We provide the possibility to navigate in time with a temporal slider. Moving in time changes the display state of 3D objects which can be in known states or in transitions between these states (creations, modifications, and demolitions). With UD-SV, our goal is to go beyond the classical dimensions of the urban model, i.e. its geometry and

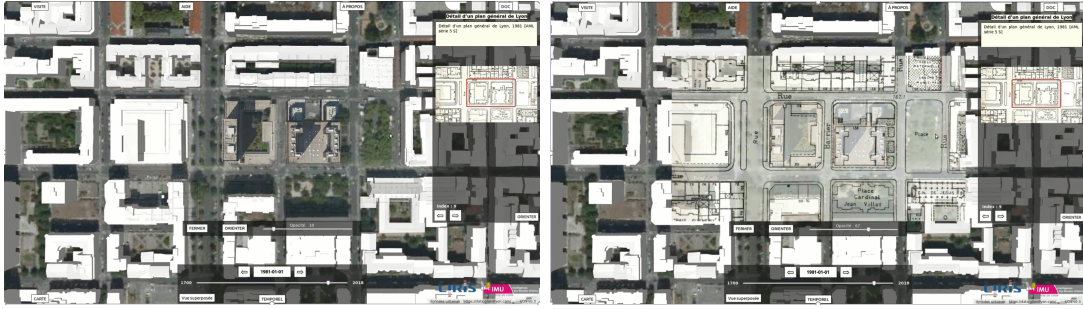


Figure 4: Multimedia sources management and visualization. The building plans are superimposed over the 3D buildings in the UD-SV. With the use of opacity values, it is also possible to see the building (roofs) underneath.

show other information like the semantic information of city objects, the hierarchy between objects, etc. We designed the following forms of access to multimedia documents [Jaillot et al., 2021] (Figure 4):

- Through a 4D spatio-temporal visualization interface (documents in superimposition to the 4D scene)
- Through thematic / semantic / metadata search
- Through guided tours
- Through linking / integration of semantic 3D city models and documents

Guided Tours UD-SV also provides guided tours, where the users do not move the temporal cursor or change the camera position but are rather automatically driven to virtual navigation in a 4D (3D + time) representation of the city, supported by documents. In a guided tour, a specific urban area or specific city objects of a given time period are shown to the user along with the available documents. With the help of clickable buttons, the user can then click to navigate

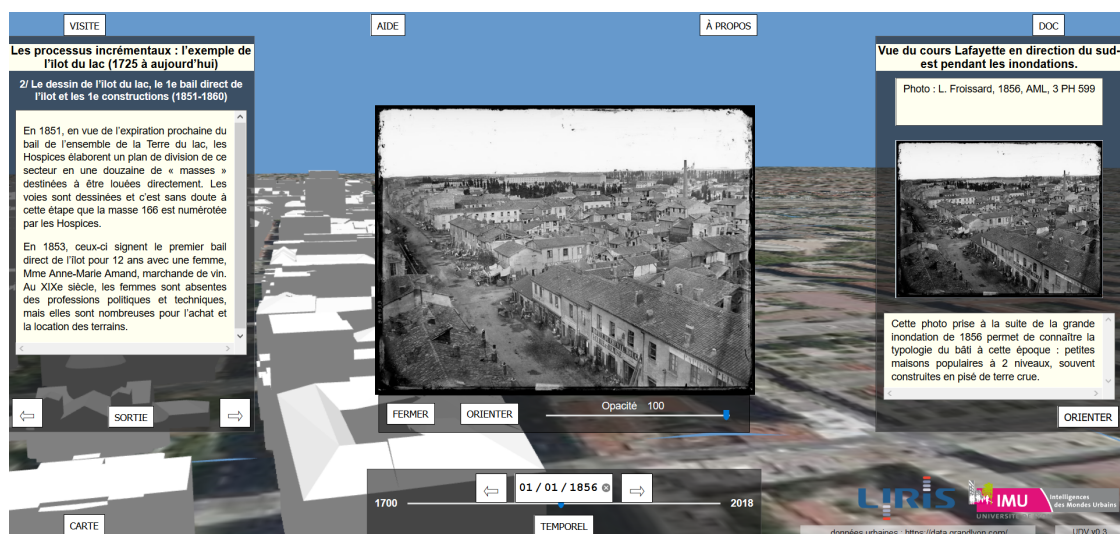


Figure 5: Guided tours in UD-SV. This shows a particular stop in the tour on January 1, 1856, highlighting not only the urban objects of interest in the background but also the documents in the foreground related to these objects in this particular time period.

to the next or previous (4D) scene. Every such (4D) scene is called a step. It is worth mentioning here that the document could be an image or a video.

A step consists of a document, a position and rotation (in the 3D scene), a date, and a descriptive text. The user can move from step to step using navigable buttons like "previous step" and "next step". The movement from the step A position to the step B position is scripted (no user input is required). The camera (which is in oriented camera mode) is smoothly translated and rotated from step A to step B. The guided tour gives a visual representation of the evolution of the city, from step A date to step B date (Figure 5).

Some recent products have integrated the notion of Story (e.g., ESRI³, Cesium⁴). Taking the idea of these "stories", UD-SV has something similar to the

³<https://www.esri.com/en-us/arcgis/products/arcgis-storymaps/overview>

⁴<https://cesium.com/blog/2020/01/28/cesium-stories/>

presentation mode of slides. This functionality allows users to prepare and broadcast stories.

3.3 Demonstration

Consider a use-case of a historian wishing to demonstrate some major historical locations and the associated photographs. They make use of some of the major widgets⁵ in UD-SV. After creating an account on UD-SV, they add multimedia documents to UD-SV and link each document to one or more city objects. Furthermore, they can visualize, navigate and interact with the 3D structures of buildings. They can also query and interact with the existing document corpus and see the associated city objects. Furthermore, they can also see the integration of other sources like transport lines, move directly to a specific location address, get additional information about building objects, obtain the details of the camera location, and choose desired layers. They can save the camera position for directly navigating to the desired location in future visits. With the temporal extension, they can also demonstrate the changes that occurred in the city.

3.4 Reuse, reproducibility and interoperability

The need for reproducibility and replicability in geospatial research because of the tremendous amount of information produced by collaboration, computation, and data acquisition processes has been highlighted by Kedron et al. [2020]. The authors consider the approach of sharing data and code related to different geospatial projects as a necessary measure towards this.

⁵<https://ud-viz.vcityliris.data.alpha.grandlyon.com/examples/AllWidget/example.html>

There have been growing efforts to ensure the reproducibility of software code in research works. One such proposition is the use of Software Heritage [Cosmo and Zacchioli, 2017] aimed for not only preserving the software heritage but also for obtaining persistent identifiers for the source code. Researchers can precisely specify the persistent identifiers of a software version for the reproducibility of the published work. Another major example is Zenodo [O’Donnell et al., 2018] which is used for obtaining the persistent identifiers of both source code and the datasets. However, it is important to state that the scientific community is slowly catching up with these possibilities.

One important aspect of UD-SV is the ensuring of reproducible, reusable, and interoperable implementations. Reproducibility refers to the ability to reproduce the results presented in this article. Reusability refers to proposing contributions (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. We have conceived and applied a method to achieve these goals.

The **interoperability** has been mainly achieved by using and extending **standards** whenever possible. For the purpose of interoperability, we used standards like CityGML [Kolbe, 2009], WFS for other vectorial data and WMS for rasters.

Persistent Identifiers and Documentation: Regarding **reusability**, the best effort has been made to ensure **contributions to existing software components** (e.g. iTowns and py3Dtiles) used by research and industry. In addition, all the software produced in the context of this work is **open source** (under the LGPL license). Moreover, we have done our best to provide **documentation** describing software conception and developments. This documentation is structured

S.No.	Name	SWHID
1.	UD-SV	<code>swh:1:dir:65963235ff00a37088b1b93283a896f4445c0cf4</code>
2.	UD-Reproducibility	<code>swh:1:dir:3aa1541cdf3f05bb1a1409f7afb314ebc19ee2cd</code>
3.	3DUSE	<code>swh:1:rev:0d643ee09460a7e3f594d5530eb0f0926286c6ab</code>
4.	py3Dtiles	<code>swh:1:rev:bf28341f32998ddd96387da90dcfb63fa6133ce6</code>
5.	UD-Viz	<code>swh:1:rev:b5a523825862a3f2dd440c2922485cdd30009834</code>
6.	UD-Serv	<code>swh:1:rev:c89553bf9098246f59ec68df2b12501f698aff77</code>
7.	iTowns	<code>swh:1:rev:e996369f1da742b8ca923f4c64d656f8d1a537db</code>

Table 2: SoftWare Heritage persistent IDentifiers (SWHIDs) of different components

in *Needs*, *Issues*, and *Design Notes*. *Needs* give information about the use case (user story), the impact of the development, the maturity, and the evaluation of the development cost. *Issues* allow us 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 methodology [Highsmith and Cockburn, 2002], currently used in many computer science companies to work with short cycles of development. In addition, architecture documentation and tutorials have been produced. All this documentation has been made openly available. 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). We believe that producing such documentation can be a step forward in making research software development reusable.

Finally, we ensure the **reproducibility** of UD-SV experiments and demonstrations [Jaillot et al., 2021] by using Software Heritage archive for persistent identifiers of software versions, Zenodo [Zenodo] for data and use of shell and Docker [Docker] with installation and usage instructions detailed in *UD-Reproducibility*. Table 1 gives the SWHID (Software Heritage Identifiers) of the various compo-

nents presented in this article. These identifiers refer to the specific revision or directory of the component and can be obtained through the search interface of Software Heritage⁶ simply by entering the identifier given in the table.

The demonstrations are also available on the website of Grand Lyon (Metropole of Lyon)^{7 8}.

3.5 Current Limitations

UD-SV has several limitations. There is a need to work on reproducibility to allow simpler use of each component and its possible composition with the other ones. We are currently working towards this by Dockerizing several components and adding new ones like, for instance, a geographic data server (geoserver). Docker containers and images help us to document and record the exact configuration in which the componets could be run. The configuration information includes the underlying operating systems, package versions to be installed, internet port numbers to be used, a series of commands required to run a component, etc. Running a Docker configuration file therefore means to automatically build the exact environment proposed by the developers. This is quite useful for reproducibility of UD-SV experiments and demonstrations. We also have to explore more on navigation based on space and time. For example, we are currently working on visualization modes based on graphs [Vinasco-Alvarez et al., 2021]. More integration of other types of data (2D/ 3D, at different scales, e.g., building scale, urban scale, etc) including vector data (road, railway lines etc.) is also being explored. A limited set of experiments have already been made on rivers, 3D terrain, roads,

⁶<https://archive.softwareheritage.org/browse/search/>

⁷<https://ud-viz.vcityliris.data.alpha.grandlyon.com/>

⁸<https://spatial-multimedia-demo.vcityliris.data.alpha.grandlyon.com/>

railways, and vegetation. Document search is currently missing. The possibility to embed 3D content (especially UD-Viz in other websites to provide additional information on 3D Urban data (for instance, using HTML IFrames) is also under consideration to enhance possible story telling in content management systems (CMS). We are currently exploring different possible representations of the city, i.e., multiscale, geometric and temporal view (with different levels of detail and levels of abstraction) and a graph based representation. This may provide users the possibility to navigate in space, time, multiple levels and data (semantic, thematic, etc.)

3.6 Future work

Our future work involves exploring the possibility to enhancing building communities around each of the components described in the article. The LGPL licence used for this development promotes the utilization of the atomic components, and associated feedback may enrich the research in the field that we are already sharing some of the components with the industry and other researchers. We expect to complete the number of components of dedicated tools for digital twins so that diverse stakeholders can easily use them with their own data. We are currently working on new components: managing a territory at several scales, from the interior of the building to the regional level in order to ensure a continuum and to allow the aggregation of third-party data from the city around 3D data, for example, linked open data and multimedia data

We are also working towards a dynamic approach where these components can find their place within the community. To do this, we rely on already identified

collectives to maintain our components. We continue the process of transferring these geo-commons⁹ to the IGN (French Mapping Agency), but also companies specialized in free software such as Oslandia.

4 Conclusion

In this article, we presented UD-SV (Urban Data - Services and Visualization), an extensible **open-source web-based framework** for visualizing and navigating 4D urban digital twin based on **open standards** and developed using **open-source web technologies**. Often guided by a **use-case-driven approach**, this framework makes it possible to propose algorithms derived from research to users without having significant computer skills. The ALARIC project, for example, helped to understand the requirements of urban planners and historians for managing and representing the concurrent viewpoints of evolving urban landscape. This article presented the functionalities of the framework that we would like to share with the larger community.

Based on our desired methodology presented in Figure 2, we demonstrated how it is implemented in UD-SV as shown in Figure 6. All our discussions and studies are documented in our internal Wikis. Component-based design and development are used to produce results and enhance UD-SV. The produced results are shared as technical reports (or preprints), published conference proceedings, or journal articles. These are also made available on our official website. All these constitute a regular research cycle. However, with UD-SV, we go further and share the code, data, and knowledge of every component publicly with an open license. To

⁹<https://www.ign.fr/la-demarche-geocommuns>

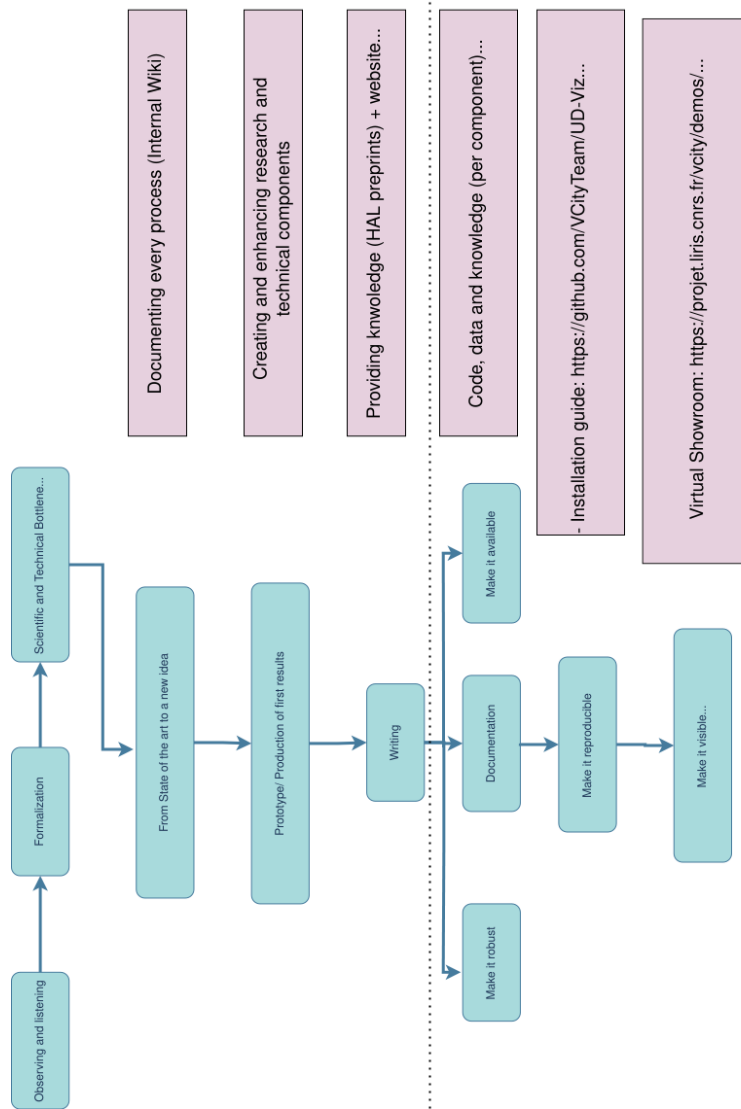


Figure 6: The methodology proposed and used in UD-SV. The boxes on the right show the approach used by the UD-SV project to respond to the various steps identified in Figure 2. UD-SV ensures that the code, data, and knowledge of every component are available publicly with an open license.

ensure the reproducibility of our works, we also share detailed documentation that helps users to build applications to their needs with desired components and/or reproduce the published scientific results. Furthermore, the demonstrations are shared on our official websites and the websites of our partner organizations.

UD-SV is built to share experimentation and ensure **reproducibility**. Dockerisation allows us to answer the use-case demands by easily composing the necessary components. Data are also provided using a framework based on persistent identifiers. Dedicated **open documentation** is also provided to lower the learning curve. The use of international standards for representing urban data ensures data **interoperability**. We also ensured to **reuse** of existing components as much as possible to reduce development costs.

Acknowledgements

We would like to thank the interns, engineers, doctoral and post-doctoral researchers who have contributed to the development of UD-SV framework during the past several years. This work was also partly supported by the LABEX IMU (ANR-10-LABX-0088) of Univ. Lyon, as part of the program ‘Investissements d’Avenir’ (ANR-11-IDEX-0007) operated by the French National Research Agency (ANR).

Code availability

- Name of the code/library: UD-SV
- Associated libraries: UD-Viz, UD-Reproducibility, UD-Serv

- Contact: gilles.gesquiere@univ-lyon2.fr
- Hardware requirements: Linux, Windows and MAC
- Program language: Python, Javascript, HTML, CSS
- Software required: Docker, Python and Javascript libraries
- Program size (lines of code obtained from *cloc*): UD-SV (≈ 10000), UD-Serv (≈ 2000), UD-Reproducibility (≈ 9000), UD-Viz (≈ 1200000)

The versions of source code referenced in this article is given in Table 1.

CRedit authorship contribution statement

- John Samuel: Conceptualization, Formal analysis, Writing-Original Draft, Writing - Review and Editing, Supervision.
- Vincent Jaillot: Conceptualization, Methodology, Writing - Original Draft, Writing - Review and Editing, Software, Validation.
- Clément Colin: Software, Validation. Diego Vinasco Alvarez: Software, Validation.
- Eric Boix: Software, Validation.
- Sylvie Servigne: Conceptualization, Formal analysis, Methodology, Writing - Original Draft, Writing - Review and Editing, Supervision.
- Gilles Gesquière: Conceptualization, Formal analysis, Methodology, Writing - Review and Editing, Project administration, Funding acquisition, Supervision.

References

- A. Albayati, N. F. Abdullah, A. Abu-Samah, A. H. Mutlag, and R. Nordin. Smart Grid Data Management in a Heterogeneous Environment with a Hybrid Load Forecasting Model. *Applied Sciences*, 11(20):9600, Oct. 2021. ISSN 2076-3417. doi: 10.3390/app11209600. URL <https://www.mdpi.com/2076-3417/11/20/9600>.
- C. Beil and T. H. Kolbe. CityGML and the streets of New York - A proposal for detailed street space modelling. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-4/W5:9–16, Oct. 2017. ISSN 2194-9050. doi: 10.5194/isprs-annals-IV-4-W5-9-2017. URL <https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/IV-4-W5/9/2017/>.
- C. Chagnaud, J. Samuel, S. Servigne, and G. Gesquière. Visualization of Documented 3D Cities. In V. Tourre and F. Biljecki, editors, *Eurographics Workshop on Urban Data Modelling and Visualisation*. The Eurographics Association, 2016. ISBN 978-3-03868-013-0. doi: 10.2312/udmv.20161425.
- K. Chaturvedi and T. H. Kolbe. A requirement analysis on extending semantic 3d city models for supporting time-dependent properties. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-4/W9:19–26, 2019. doi: 10.5194/isprs-annals-IV-4-W9-19-2019. URL <https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/IV-4-W9/19/2019/>.
- K. Chaturvedi, C. S. Smyth, G. Gesquière, T. Kutzner, and T. H. Kolbe. *Managing*

- Versions and History Within Semantic 3D City Models for the Next Generation of CityGML*, pages 191–206. Springer International Publishing, Cham, 2017. ISBN 978-3-319-25691-7. doi: 10.1007/978-3-319-25691-7_11. URL https://doi.org/10.1007/978-3-319-25691-7_11.
- R. D. Cosmo and S. Zacchioli. Software heritage: Why and how to preserve software source code. In S. Hara, S. Sugimoto, and M. Goto, editors, *Proceedings of the 14th International Conference on Digital Preservation, iPRES 2017, Kyoto, Japan, September 25-29, 2017*, 2017. URL <https://hdl.handle.net/11353/10.931064>.
- B. De Roo, J. Bourgeois, and P. De Maeyer. On the way to a 4d archaeological gis: state of the art, future directions and need for standardization. In A. C. Addison, L. De Luca, G. Guidi, and S. Pescarin, editors, *Proceedings of the 2013 digital heritage international congress*, volume 2, pages 617–620. Institute of Electrical and Electronics Engineers (IEEE), 2013. ISBN 9781479931699.
- F. Dembski, U. Wössner, M. Letzgus, M. Ruddat, and C. Yamu. Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg, Germany. *Sustainability*, 12(6):2307, Mar. 2020. ISSN 2071-1050. doi: 10.3390/su12062307. URL <https://www.mdpi.com/2071-1050/12/6/2307>.
- L. Dewitz, C. Kröber, H. Messemer, F. Maiwald, S. Münster, J. Bruschke, and F. Niebling. Historical photos and visualizations: Potential for research. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W15:405–412, 2019. doi: 10.5194/isprs-archives-XLII-2-W15-405-2019.

URL <https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-2-W15/405/2019/>.

Docker. Docker. <https://www.docker.com/>.

S. Evans, A. Hudson-Smith, and M. Batty. 3-D GIS: Virtual London and beyond: An exploration of the 3-D GIS experience involved in the creation of Virtual London. *Cybergeo*, Oct. 2006. ISSN 1278-3366. doi: 10.4000/cybergeo.2871. URL <http://journals.openedition.org/cybergeo/2871>.

K. Friedrichs, S. Münster, C. Kröber, and J. Brusckke. Creating Suitable Tools for Art and Architectural Research with Historic Media Repositories. In S. Münster, K. Friedrichs, F. Niebling, and A. Seidel-Grzesińska, editors, *Digital Research and Education in Architectural Heritage*, Communications in Computer and Information Science, pages 117–138. Springer International Publishing, 2018. ISBN 978-3-319-76992-9.

J. Gaillard, A. Peytavie, and G. Gesquière. Visualisation and personalisation of multi-representations city models. *International Journal of Digital Earth*, 13(5): 627–644, May 2020. ISSN 1753-8947. doi: 10.1080/17538947.2018.1550122. URL <https://www.tandfonline.com/doi/10.1080/17538947.2018.1550122>.

G. Gesquière and A. Manin. 3D Visualization of Urban Data Based on CityGML with WebGL. *International Journal of 3-D Information Modeling (IJ3DIM)*, 1(3):1–15, 2012. ISSN 2156-1710. doi: 10.4018/ij3dim.2012070101. URL <https://www.igi-global.com/gateway/article/www.igi-global.com/gateway/article/70401>.

- G. Gröger and L. Plümer. Citygml – interoperable semantic 3d city models. *ISPRS Journal of Photogrammetry and Remote Sensing*, 71:12 – 33, 2012. ISSN 0924-2716. doi: <https://doi.org/10.1016/j.isprsjprs.2012.04.004>. URL <http://www.sciencedirect.com/science/article/pii/S0924271612000779>.
- J. Highsmith and A. Cockburn. What is agile software development? *The Journal of Defense Software Engineering*, 15(10):4–9, 2002.
- IGN. Ign. <https://www.ign.fr/>.
- International Organization for Standardization. Geographic information - Terminology. Standard ISO 19104:2008, Nov. 2008. URL <https://www.iso.org/standard/63541.html>.
- V. Jaillot. *3D, temporal and documented cities : formalization, visualization and navigation*. phdthesis, Université de Lyon, Sept. 2020. URL <https://tel.archives-ouvertes.fr/tel-03228436>.
- V. Jaillot, M. Istasse, S. Servigne, G. Gesquière, M. Rautenberg, and I. Lefort. Describing, comparing and analysing digital urban heritage tools: A methodology designed with a multidisciplinary approach. *Digital Applications in Archaeology and Cultural Heritage*, 17:e00135, June 2020a. ISSN 2212-0548. doi: 10.1016/j.daach.2020.e00135. URL <http://www.sciencedirect.com/science/article/pii/S2212054819300633>.
- V. Jaillot, S. Servigne, and G. Gesquière. Delivering time-evolving 3D city models for web visualization. *International Journal of Geographical Information Science*, pages 1–23, Apr. 2020b. ISSN 1365-8816, 1362-3087. doi:

- 10.1080/13658816.2020.1749637. URL <https://www.tandfonline.com/doi/full/10.1080/13658816.2020.1749637>.
- V. Jaillot, V. Rigolle, S. Servigne, J. Samuel, and G. Gesquière. Integrating multimedia documents and time-evolving 3d city models for web visualization and navigation. *Transactions in GIS*, 25(3):1419–1438, 2021. doi: <https://doi.org/10.1111/tgis.12734>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/tgis.12734>.
- F. Kaplan. The venice time machine. In *Proceedings of the 2015 ACM Symposium on Document Engineering, DocEng '15*, pages 73–73. ACM, 2015. ISBN 978-1-4503-3307-8. doi: 10.1145/2682571.2797071. URL <http://doi.acm.org/10.1145/2682571.2797071>.
- P. Kedron, W. Li, S. Fotheringham, and M. Goodchild. Reproducibility and replicability: opportunities and challenges for geospatial research. *International Journal of Geographical Information Science*, pages 1–19, Aug. 2020. ISSN 1365-8816, 1362-3087. doi: 10.1080/13658816.2020.1802032. URL <https://www.tandfonline.com/doi/full/10.1080/13658816.2020.1802032>.
- T. H. Kolbe. *Representing and Exchanging 3D City Models with CityGML*, pages 15–31. Springer Berlin Heidelberg, Berlin, Heidelberg, 2009. doi: 10.1007/978-3-540-87395-2_2. URL https://doi.org/10.1007/978-3-540-87395-2_2.
- T. H. Kolbe, G. Gröger, and L. Plümer. *CityGML: Interoperable Access to 3D City Models*, pages 883–899. Springer Berlin Heidelberg, Berlin, Heidelberg,

2005. ISBN 978-3-540-27468-1. doi: 10.1007/3-540-27468-5_63. URL https://doi.org/10.1007/3-540-27468-5_63.
- T. Kutzner, K. Chaturvedi, and T. H. Kolbe. CityGML 3.0: New Functions Open Up New Applications. *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, Feb. 2020. ISSN 2512-2789, 2512-2819. doi: 10.1007/s41064-020-00095-z. URL <http://link.springer.com/10.1007/s41064-020-00095-z>.
- A. Königer and S. Bartel. 3d-gis for urban purposes. *Geoinformatica*, 2(1): 79–103, 1998. ISSN 13846175. doi: 10.1023/A:1009797106866. URL <http://link.springer.com/10.1023/A:1009797106866>.
- Z. Lei, H. Zhou, W. Hu, and G.-P. Liu. Web-based digital twin online laboratories: Methodologies and implementation. *Digital Twin*, 2:3, Mar. 2022. ISSN 2752-5783. doi: 10.12688/digitaltwin.17563.1. URL <https://digitaltwin1.org/articles/2-3/v1>.
- F. Maiwald, F. Henze, J. Brusckke, and F. Niebling. Geo-information technologies for a multimodal access on historical photographs and maps for research and communication in urban history. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W11:763–769, May 2019. ISSN 2194-9034. doi: 10.5194/isprs-archives-XLII-2-W11-763-2019. URL <https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-2-W11/763/2019/>.
- R. Miao, J. Song, and Y. Zhu. 3d geographic scenes visualization based on webgl.

- In *2017 6th International Conference on Agro-Geoinformatics*, pages 1–6, 2017. doi: 10.1109/Agro-Geoinformatics.2017.8046999.
- S. Münster, F. Niebling, J. Bruschke, K. Barthel, K. Friedrichs, C. Kröber, and F. Maiwald. *Urban History Research and Discovery in the Age of Digital Repositories. A Report About Users and Requirements*, pages 63–84. Springer International Publishing, Cham, 2020. ISBN 978-3-030-15200-0. doi: 10.1007/978-3-030-15200-0_5. URL https://doi.org/10.1007/978-3-030-15200-0_5.
- T. Nakaya, K. Yano, Y. Isoda, T. Kawasumi, Y. Takase, T. Kirimura, A. Tsukamoto, A. Matsumoto, T. Seto, and T. Iizuka. *Virtual Kyoto Project: Digital Diorama of the Past, Present, and Future of the Historical City of Kyoto*, pages 173–187. Springer Berlin Heidelberg, Berlin, Heidelberg, 2010. ISBN 978-3-642-17184-0. doi: 10.1007/978-3-642-17184-0_14. URL https://doi.org/10.1007/978-3-642-17184-0_14.
- A. Nurminen and A. Oulasvirta. *Designing Interactions for Navigation in 3D Mobile Maps*, pages 198–227. Springer Berlin Heidelberg, Berlin, Heidelberg, 2008. ISBN 978-3-540-37110-6. doi: 10.1007/978-3-540-37110-6_10. URL https://doi.org/10.1007/978-3-540-37110-6_10.
- D. P. O’Donnell, N. Manola, P. Manghi, D. Porter, P. Esau, C. Viejou, R. R. D. Turco, and G. Singh. Using zenodo as a discovery and publishing platform. In J. G. Palau and I. G. Russell, editors, *13th Annual International Conference of the Alliance of Digital Humanities Organizations, DH 2018, Mexico City, Mexico, June 26-29, 2018, Conference Abstracts*, page 645. Red de

- Humanidades Digitales A. C., 2018. URL <https://dh2018.adho.org/en/using-zenodo-as-a-discovery-and-publishing-platform/>.
- OGC. Citygml. <https://www.ogc.org/standards/citygml>, a.
- OGC. Glossary of terms - f. <https://www.ogc.org/ogc/glossary/f>, b.
- OpenStreetMap. Openstreetmap. <https://www.openstreetmap.org/>.
- Oslandia. Oslandia. <https://oslandia.com/en/>.
- D. Pacheco, S. Wierenga, P. Omedas, S. Wilbricht, H. Knoch, and P. F. M. J. Verschure. Spatializing experience: a framework for the geolocalization, visualization and exploration of historical data using VR/AR technologies. In *Proceedings of the 2014 Virtual Reality International Conference on - VRIC '14*, pages 1–4, Laval, France, 2014. ACM Press. ISBN 9781450326261. doi: 10.1145/2617841.2617842. URL <http://dl.acm.org/citation.cfm?doid=2617841.2617842>.
- M. Pfeiffer, C. Carré, V. Delfosse, P. Hallot, and R. Billen. Virtual leodium: from an historical 3d city scale model to an archaeological information system. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, II-5/W1:241–246, 2013. doi: 10.5194/isprsannals-II-5-W1-241-2013. URL <https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/II-5-W1/241/2013/>.
- I. Pispidikis and E. Dimopoulou. Development of a 3d webgis system for retrieving and visualizing citygml data based on their geometric and semantic characteristics by using free and open source technology. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-2/W1:47–

- 53, Oct. 2016. ISSN 2194-9050. doi: 10.5194/isprs-annals-IV-2-W1-47-2016. URL <http://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/IV-2-W1/47/2016/>.
- S. Rizvic, V. Okanovic, and A. Sadzak. Visualization and multimedia presentation of cultural heritage. In *2015 38th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)*, pages 348–351, May 2015. doi: 10.1109/MIPRO.2015.7160292.
- J. Samuel, C. Périnaud, S. Servigne, G. Gay, and G. Gesquière. Representation and Visualization of Urban Fabric through Historical Documents. In C. E. Catalano and L. D. Luca, editors, *Eurographics Workshop on Graphics and Cultural Heritage*. The Eurographics Association, 2016. ISBN 978-3-03868-011-6. doi: 10.2312/gch.20161399.
- J. Samuel, S. Servigne, and G. Gesquière. Representation of concurrent points of view of urban changes for city models. *Journal of Geographical Systems*, Feb. 2020. ISSN 1435-5930, 1435-5949. doi: 10.1007/s10109-020-00319-1. URL <http://link.springer.com/10.1007/s10109-020-00319-1>.
- G. Schindler and F. Dellaert. 4d Cities: Analyzing, Visualizing, and Interacting with Historical Urban Photo Collections. *Journal of Multimedia*, 7(2):124–131, Apr. 2012. ISSN 1796-2048. doi: 10.4304/jmm.7.2.124-131. URL <http://ojs.academypublisher.com/index.php/jmm/article/view/7118>.
- N. Shiode. 3d urban models: Recent developments in the digital modelling of urban environments in three-dimensions. *GeoJournal*, 52(3):263–269, 11 2000.

ISSN 1572-9893. doi: 10.1023/A:1014276309416. URL <https://doi.org/10.1023/A:1014276309416>.

P. Smith. Bim implementation – global strategies. *Procedia Engineering*, 85: 482 – 492, 2014. ISSN 1877-7058. doi: <https://doi.org/10.1016/j.proeng.2014.10.575>. URL <http://www.sciencedirect.com/science/article/pii/S1877705814019419>. Selected papers from Creative Construction Conference 2014.

N. Snavely, S. M. Seitz, and R. Szeliski. Photo Tourism: Exploring Photo Collections in 3d. In *ACM SIGGRAPH 2006 Papers*, SIGGRAPH '06, pages 835–846, New York, NY, USA, 2006. ACM. ISBN 978-1-59593-364-5. doi: 10.1145/1179352.1141964. URL <http://doi.acm.org/10.1145/1179352.1141964>. event-place: Boston, Massachusetts.

C. Stefani, C. Busayarat, J. Lombardo, L. D. Luca, and P. Véron. A web platform for the consultation of spatialized and semantically enriched iconographic sources on cultural heritage buildings. *Journal on Computing and Cultural Heritage (JOCCH)*, 6(3):13, 2013.

D. Vinasco-Alvarez, J. Samuel, S. Servigne, and G. Gesquière. Towards limiting semantic data loss in 4D urban data semantic graph generation. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, VIII-4/W2-2021:37–44, 2021. doi: 10.5194/isprs-annals-VIII-4-W2-2021-37-2021. URL <https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/VIII-4-W2-2021/37/2021/>.

Zenodo. Zenodo. <https://zenodo.org/>.

L. Zhang, C. Han, L. Zhang, X. Zhang, and J. Li. Web-based visualization of large 3d urban building models. *International Journal of Digital Earth*, 7(1): 53–67, Jan. 2014. ISSN 1753-8947, 1753-8955. doi: 10.1080/17538947.2012.667159. URL <http://www.tandfonline.com/doi/abs/10.1080/17538947.2012.667159>.

G. Zhou, Z. Tan, M. Cen, and C. Li. Customizing Visualization in Three-Dimensional Urban GIS via Web-Based Interaction. *Journal of Urban Planning and Development*, 132(2):97–103, June 2006. ISSN 0733-9488, 1943-5444. doi: 10.1061/(ASCE)0733-9488(2006)132:2(97). URL <http://ascelibrary.org/doi/10.1061/%28ASCE%290733-9488%282006%29132%3A2%2897%29>.