BUILDSPACE

Enabling Innovative Space-driven Services for Energy Efficient Buildings and Climate Resilient Cities

D3.1 BUILDSPACE core platform and services

February 2024

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Abbreviations and acronyms

Acronym	Description
3D	Three dimensions
API	Application Programming Interface
AR	Augmented Reality
BGI	Blue-Green Infrastructure
BIM	Building Information Model
BVC	Buildings Value Chain
CDH	Cooling Degree Hours
CGAL	Computational Geometry Algorithms Library
CityGML	City Geography Markup Language
CMIP6	Coupled Model Intercomparison Project Phase 6
D	Deliverable
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DT	Digital Twin
DSM	Digital Surface Model
DTM	Digital Terrain Model
EGNSS	European Global Navigation Satellite System
EOSC	European Open Science Cloud
EPC	Energy Performance Certificate
FDAM	Flood Damage Assessment Methodology
GA	Grant Agreement
gDT	geometric Digital Twin
GIS	Geographical Information System
GNNS	Graph Neural Networks
GPS	Global Positioning System

Acronym	Description
HDH	Heating Degree Hours
HTTP	Hypertext Transfer Protocol
IFC	International Foundation Class
IoT	Internet of Things
JWT	JSON Web Token
KPI	Key Performance Indicator
LAS	LIDAR Aerial Survey
LiDAR	Light Detection and Ranging (or Laser Imaging Detection and Ranging)
LOD	Level of Detail
M	Month
ML	Machine Learning
NDVI	Normalized Difference Vegetation Index
NetCDF	Network Common Data Form
OIDC	OpenID Connect
OSM	OpenStreetMap
PCL	Point Cloud Library
PLY	PoLYgon file format
PV	Photovoltaic
RANSAC	Random Sample Consensus
RCP	Representative Concentration Pathway
REST	REpresentational State Transfer
RGB	Red, Green, Blue
RTK	Real-Time Kinematic
SE	Service
SLAM	Simultaneous Localization and Mapping

Acronym	Description
SSP	Shared Socioeconomic Pathway
T	Task
U	Value for thermal transmittance
UAV	Unmanned Aerial Vehicle
UC	Use Case
UCZ	Urban Climate Zones
UHE	Urban Heat Exposure
UHR	Urban Heat Risk
UHV	Urban Heat Vulnerability
UI	User Interface
VM	Virtual Machine
VR	Virtual Reality
WP	Work Package
XR	Extended Reality
YAML	Yet Another Markup Language
YOLO	You Only Look Once

Table of Contents

List of Tables

List of Figures

Executive summary

The EU-funded BUILDSPACE project aims to support Green Deal objectives by **developing innovative applications** to support **buildings' energy efficiency** and **cities' resilience and sustainability**. The project provides **services** to enable users to interact with a **building's digital twin** and the city's stakeholders to effectively develop **strategies for the sustainability and resilience of cities** against the risk posed by climate change, with an emphasis on the analysis of the energy performance, urban heat and flooding.

These **services, as decision support tools**, will be offered through a **Core Platform**, which will allow the integration of the heterogeneous data from buildings (collected by IoT platforms, BIM solutions and other) with aerial imaging from drones, as well as from satellite services such as EGNSS and Copernicus.

The **Work Package (WP) 3 "BUILDSPACE location-based and remote sensing applications development"** coordinates and carries out the specific activities to ensure the development, deployment and validation of the BUILDSPACE platform and services. It creates the interoperable platform that offers added value services at building and at city scale. These services will enable buildings' monitoring at different stages (construction, operation, renovation) and allow their linking to city scale services enabling analysis and prediction of the urban environment considering climate change.

Services at building scale enable the **Digital Twin (DT) generation** of the building (**SE1**) and its **semantic enrichment** (**SE2**) with thermography data collected by drones to support building construction (through AR/VR features of DTs at construction sites) as well as building renovation and monitoring. **Services at city scale** rely on a mix of Copernicus and IoT data to infer visualisations related to **energy demand** (**SE3**), **urban heat** (**SE4**) and **urban flood** (**SE5**) analysis and assessment, facilitating decision making for increased resilience of the building stock.

The deliverable 3.1 "BUILDSPACE core platform and services" is the **first iteration of the BUILDSPACE core platform and services**, where the **first technology release** is presented. Thus, the D3.1 introduces the objectives pursued in WP3 and in the different tasks, as well as the methodology and the delivery plan in the three technology releases (section **1**). Then, it presents the Core Platform in section **2**, which is based on the Conceptual Architecture (section **2.1**), detailing the overview and specifications of the platform (section **2.2**) and its infrastructure (section **2.3**). In sections **3** to **6**, the different services are depicted, including a description of its components and functionalities, as well as references to the related use cases. Furthermore, each section is divided into sub-sections to provide further detail on services inputs and outputs, the service workflow and the application of the services in the project pilots, together with the current progress up to the current 1st technical release.

Finally, the document includes also two guides developed in the context of the Digital Twin services, one for building recommendations for drone flights (section **9**), and the other for technical requirements for data collection (including also further details for both services SE1 and SE2), in section **10**.

1. Introduction

BUILDSPACE aims to support Green Deal objectives by developing innovative applications to support buildings' energy efficiency and cities' resilience and sustainability. Through cutting-edge technologies, such as satellite data analysis, digital twins, virtual and augmented reality (AR/VR), and drones equipped with thermal cameras, the project provides services to enable users to interact with a building's digital twin. It also allows the city's stakeholders to effectively monitor the energy performance of the city's buildings to develop strategies for the suitability and resilience of cities against the risk posed by climate change, with an emphasis on the analysis of the urban thermal environment and flooding.

The BUILDSPACE platform will allow integration of the heterogeneous data from buildings (collected by IoT platforms, BIM solutions and other) with aerial imaging from drones, as well as from satellite services (i.e. EGNSS and Copernicus); and will offer a range of decision support tools (five services) applied from building to urban scale to the Buildings Value Chain (BVC) stakeholders

WP3 "BUILDSPACE location-based and remote sensing applications development" aims at coordinating and carrying out the specific activities to ensure the development, deployment and validation of the BUILDSPACE platform and services. It specifically aims to achieve the following **objectives**:

1. To create the specifications and architecture defined under WP2;
2. To implement the core BUILDSPACE platform integrating the heterogeneous data sets and make them available through a common interface;
3. To perform the technical development and integration of the different platform services for the 2 levels addressed in BUILDSPACE (building level (T3.2), city level (T3.3-T3.5));
4. To deploy and test the platform from a technical point of view.

The main **concept** of WP3 is to create an interoperable core platform in which added value services at building and city scale (Figure 1) are offered. These services will enable buildings' monitoring at different stages (construction, operation, renovation) and allow their linking to city scale services enabling analysis and prediction of urban environment considering climate change.

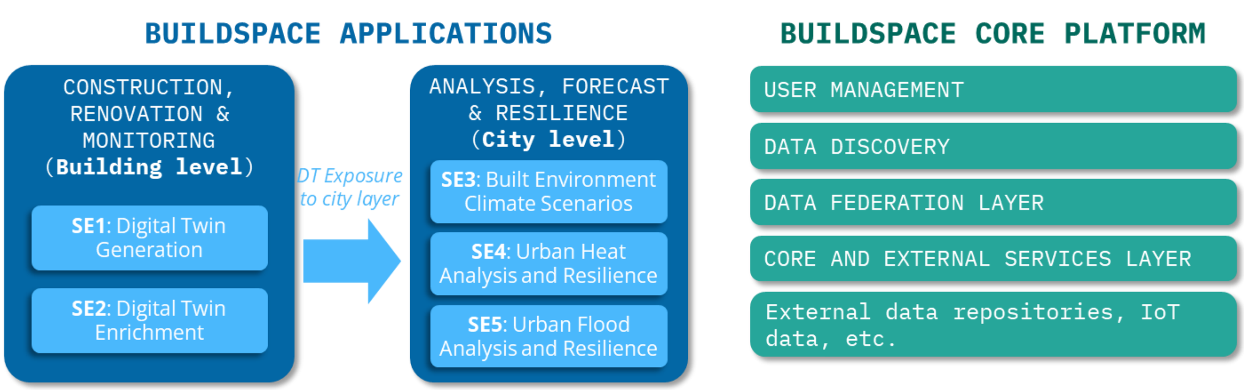


Figure 1. BUILDSPACE concept for applications and core platform

Thus, the **services** are divided into building level and city level categories:

- The **services at building scale (SE1 and SE2)** will enable the Digital Twins (DTs) generation of buildings and its semantic enrichment with thermography data collected by drones to support building construction (through AR/VR features of DTs at construction site) as well as building renovation and monitoring.
- The **services at city scale (SE3, SE4 and SE5)** rely on a mix of Copernicus and IoT data to infer visualisations related to energy demand, urban heat and urban flood analysis and assessment at urban scales, facilitating decision making for increased resilience to climate change of the building stock.

BUILDSPACE's services will be implemented in four EU countries, which correspond to the four **pilots**:

- **Pilot 1**: Facilitating Building Construction (Poland),
- **Pilot 2**: Energy Demand Analysis, Forecast and Climate Resilience (Riga, Latvia),
- **Pilot 3**: Urban Heat Analysis and Resilience (Piraeus, Greece),
- **Pilot 4**: Urban Flood Analysis and Resilience (Ljubljana Urban Region, Slovenia).

The building level services will be widely applied across pilots: SE1 will be applied in all Pilots (with a different degree of definition), and SE2 will be applied in Pilot 1 (Poland) and in Pilot 3 (Greece). The city scale services will be then applied one to each pilot, being SE3 be applied in Pilot 2 (Latvia), SE4 in Pilot 3 (Greece) and SE5 in Pilot 5 (Slovenia).

The WP will follow the three iterative cycles of work defined in the BUILDSPACE **methodology**, and will count on releases in months 13, 21 and 28, as can be seen in Figure 2.

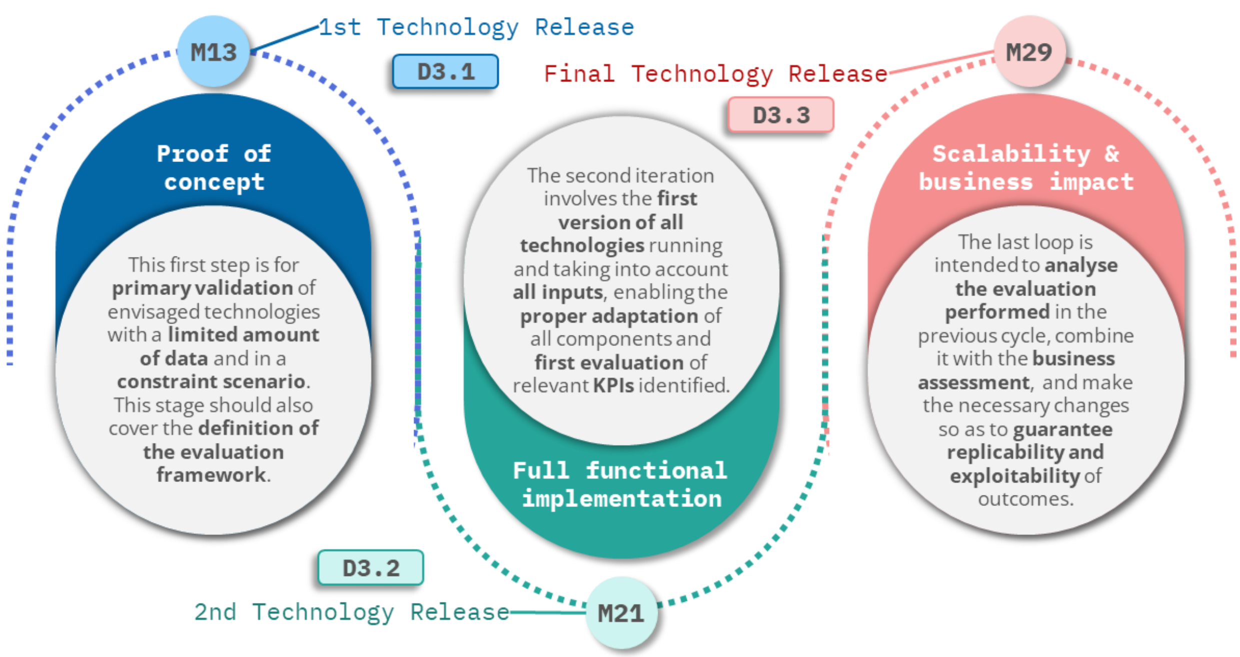


Figure 2. BUILDSPACE methodology of iterative cycles of work and related deliverables in WP3

This WP development is very much linked to the developments and progress in WP2 “BUILDSPACE requirements, co-creation, specifications and alignment with satellite services”. The user requirements were elicited (and reported in D2.1 “BUILDSPACE user requirements”) from pilots related to the different services. The alignment of the Copernicus and EGNSS data that will be used in the different services is also a key input from this WP, as well as the outcomes of the two co-creation sessions organised, involving external stakeholders to obtain valuable feedback from potential end-users.

These co-creation sessions involved both the service leaders, to explain first-hand what their service is all about. The first co-creation session started by stating some challenges and difficulties (or “pains”) that could be overcame by the services. Then, breakout groups were organised to deep dive into the service that was of most interest for the stakeholders. In the rooms, the functionalities of the services were further explained, and attendees were asked about what they need more in detail, as well as for visualisation ideas. All information about the first co-creation session is reported in deliverable 2.2 “Use cases and design of applications’ dashboards”.

This main feedback served to the other task in WP2 related to the design of the wireframes, as well as to set a first round of the use cases for each service. In the second co-creation session, the services’ functionalities were presented more in detail before the breakout groups. Then, stakeholders were divided into rooms for the different services, as in the first session (SE1 and SE2 together, and then SE3, SE4 and SE5 in different rooms). In the groups, the workflow of the services was presented and participants were asked to provide feedback on the different parts. Then, several questions were made on different topics of each service, on comparisons that could be offered, different visualisations for certain parts and other more general questions. All the details of this second session will be included in the D2.3 “BUILDSPACE specifications and architecture”, to be delivered in May 2024.

The outcomes of this second session were also considered by all services, mainly included in the formulation of the use cases (and in updated versions), which are also included in each service section for the sake of clarity and further understanding of service functionalities.

The task related to the conceptual architecture within WP2 is also a key input for the WP3, more specifically, for the development of the core platform, that needs to also include all the services. In fact, as the conceptual architecture will be reported in D2.3, for a better understanding of the core platform in the present document, an initial version of it has been included as well.

The WP4 “Demonstration of BUILDSPACE towards sustainable and resilient buildings and cities” is also quite related to the WP3 work. Mainly because it is the work package related to the pilots of the project, and the services should be validated and tested by them. The D4.1 “BUILDSPACE evaluation methodology and baseline assessment” includes a list of KPIs related to the targets that should be achieved through the implementation of the services in the pilots, which has been elaborated in agreement with service leaders and WP3 developments.

1.1. Deliverable structure

The present deliverable 3.1 "BUILDSPACE core platform and services" is the first iteration of the BUILDSPACE core platform and services, where the first release is reported. The document is **structured** in the following sections:

- **Section 1**, current section, introduces the BUILDSPACE project, WP3 objectives and concept, services and pilots, as well as the methodology. It also includes the document structure (**1.1**), and the delivery plan for the three technology releases (**1.2**).
- **Section 2** focuses on the BUILDSPACE Core Platform, based on the Conceptual Architecture (**2.1**) that is being developed under T2.5, as well as the overview and specifications of the Core Platform (**2.2**) and the Core Platform Infrastructure (**2.3**).
- Then, sections 3-6 are devoted to the BUILDSPACE services, ordered in the same way as the WP3 tasks, and with the same structure, first (for each section **X**, which corresponds to **sections 3 to 6**) providing the description and reference to the use cases, a sub-section (**X.1**) for the specification of both inputs and outputs, then (**X.2**) includes the service workflow, and finally (**X.3**) describes their application (in the project pilots) together with the current progress. These sections are:
    - **Section 3**, which includes the services at building scale: Digital Twin Generation (**SE1**) and Enrichment (**SE2**). The description of the application of the services in pilots and current progress (**3.3**) is divided into the two services to deep into the progress of each.
    - **Section 4** is for **SE3**, Built Environment Climate Scenarios, at city scale.
    - **Section 5** is devoted for the service on Urban Heat Analysis and Resilience (**SE4**), at city scale.
    - **Section 6** includes **SE5**, Urban Flood Analysis and Resilience, at city scale as well.
- **Section 7** provides the conclusions of the document.
- **Section 8** includes the references.

At the end, the document includes two annexes to include the guides developed in the context of the digital twin services (SE1 and SE2):

- **Section 9** includes the **Annex A**, with the Digital Twin Building Recommendations for Drone flight. It includes general recommendations (**9.1**) and thermal recommendations (**9.2**).
- **Section 10** is devoted to the **Annex B**, which is about the Digital Twin technical requirements for data collection. It includes a section to detail all the technical requirements (**10.1**), including both for external flight (**10.1.1**) and for indoor scanning (**10.1.2**); as well as two sections to detail the services, SE1 in section **10.2**, and SE2 in section **10.3**.

1.2. Technology releases delivery

The following Table 1, depicts the different developments of the core platform and the services that will be ready for the three different technology releases. The "Functionalities" column lists the different functionalities for the different elements, with an assigned number that is referenced in the "releases" columns. Then, in the three columns for the technology releases, the different numbers are referenced to point out the functionalities that will be released in each one. Some clarifications next to the bullet number points are made to make clear if the functionality will be ready for the release but only partly, or with simplified or initial elements.

Table 1. Relation of the platform and services with what will be delivered in each technology release

Platform / Service	Functionalities *Number assigned used as reference in the next cells of the releases*	1st Technology Release (M13 – D3.1)	2nd Technology Release (M21 – D3.2)	Final Technology Release (M29 – D3.3)
Core Platform	1. Identity provisioning 2. Intuitive User Interface (UI) 3. Data storage and data management (upload/ download/ update) 4. Data sharing mechanisms 5. Folder functionalities (creation of folders, upload files in certain folders, etc.) 6. Integration of Copernicus Land, Atmosphere, Climate Change services 7. Integration of EGNSS Galileo HAS 8. Search of datasets throughout all BUILDSPACE services	1. Fully deployed 3. Fully deployed 4. Fully developed 5. Fully developed (completely tested) 6. Fully developed (initial testing)	2. Fully developed (initial testing) 4. Completely tested 6. Completely tested 7. Fully developed (initial testing) 8. Fully developed (initial testing)	2. Completely tested 7. Completely tested 8. Completely tested Final Test of the whole platform
SE1	1. Segmentation of the 3D point cloud model 2. gDT generation of indoor environment 3. gDT generation of façade 4. gDT generation of roof 5. gDT generation of construction phase 6. EGNSS data integration 7. VR/AR-support gDT visualisation	Initial testing on 1, 2, 3, 4; and user requirements definition of, 5 and 6.	Technical development of 1, 2, 3, 4; initial testing of 4, 5, 6 and 7.	Development of 4, 5, 6, and 7; final results of all the functionalities.
SE2	1. RGB point cloud generation from photogrammetry and SLAM 2. Thermal point cloud generation from photogrammetry 3. Identification of thermal bridges in the external envelope	1. First results of the processing 2. First results of the processing	1. Final results of the processing 2. Final results of the processing	1. Final results of the processing 2. Final results of the processing

Platform / Service	Functionalities *Number assigned used as reference in the next cells of the releases*	1st Technology Release (M13 – D3.1)	2nd Technology Release (M21 – D3.2)	Final Technology Release (M29 – D3.3)
	4. Categorisation of thermal bridges according to type and report generation 5. Identification of dampness in the external envelope 6. Categorisation of dampness according to type and report generation 7. Identification of malfunctioning cells in solar panel installation 8. Categorisation of panels according to performance		3. First results 4. First results 5. First results 6. First results 7. First results 8. First results	3. Final results 4. Final results 5. Final results 6. Final results 7. Final results 8. Final results
SE3	1. Estimation of energy demand of building stock 2. Estimation of energy consumption of building stock 3. Calculation of both energy demand and consumption in future climate change scenarios 4. Representation in a coloured map of energy demand and consumption 5. GUI: user-friendly interface 6. Calculation of KPIs for energy retrofitting strategies (energy efficiency retrofitting measures) 7. Assessment of Solar PV potential 8. Integration of PV potential with retrofitting strategies, to cover heating demand with PV production (self-consumption)	1. in a district 4. in a simplified version 7. in a district (and yearly output)	1. for the whole city 2. for the whole city 3. 4. 5. first version of GUI 7. for the whole city (hourly output)	Final results of functionalities: 1. 2. 3. 4. 5. 6. 7. 8.
SE4	1. Calculation of Urban Heat Vulnerability 2. Calculation of Urban Heat Exposure 3. Calculation of Urban Heat Hazard 4. Urban Heat Risk hotspots identification map 5. Identification of areas with higher adaptation potential map 6. Adaptation and mitigation strategies portfolio	1., 2., 3. Test of systematisation of data downloading and data management 4. NUT region level	1., 2., 3., 4., 5. City scale 6. Identification of adaptation and mitigation strategies 7. At UCZ scale 8. In a district	1., 2., 3., 4., 6.. At Sub-District Level 5. At sub-district level within hotspots 8. at city scale

Platform / Service	**Functionalities** *Number assigned used as reference in the next cells of the releases*	**1st Technology Release (M13 – D3.1)**	**2nd Technology Release (M21 – D3.2)**	**Final Technology Release (M29 – D3.3)**
	7. Creation of long temporal series of temperature and relative humidity for different Urban Climate Zones. 8. Buildings' energy demand			
SE5	1. Calculation of expected flood damages to buildings 2. Calculation of blue-green factor to land use areas 3. Calculation of runoff to land use areas 4. User-friendly interface 5. Flood damage hotspots identification map 6. Flood vulnerability hotspots identification map 7. Visualisation of expected flood damages and runoff to land use areas by graphs and tables 8. Calculation for different rainfall and retrofitting scenarios 9. Guidance with adaptation instructions	1. developed 4. first version 5. developed 7. only for exp. flood damages 8. in a simplified version	Developed: 1., 2., 3., 4., 5., 6., 7. 8. Using national climate change scenarios 9. Identification of adaptation instructions	Final results of functionalities: 1. 2. 3. 4. 5. 6. 7. 8. 9.

2. BUILDSPACE Core Platform

2.1. Conceptual Architecture

The BUILDSPACE Conceptual Architecture aims at putting together, under the same conceptual umbrella, the interconnections and interdependencies derived from the technical work that has been carried out so far within the framework of the BUILDSPACE project, towards deploying the layout for the development of the consequent BUILDSPACE Platform. The presented Conceptual Architecture takes into consideration the user requirements that have been reported in D2.1 and updated ever since (in D2.2 and D3.1, also based on the outcomes of the two stakeholder engagement co-creation sessions), as well as the resulting technical requirements. On top of that, the use cases that have been configured and discussed in D2.2 have been used as a driver to identify key technical constraints and specifications, which in turn laid the groundwork for framing the architecture's functionalities according to real-life–driven needs and priorities.

The BUILDSPACE Conceptual Architecture has been created in a way that emphasises the functional viewpoint of the architectural model, to ensure alignment with other relative well-established European standards that deal with different architectural aspects, such as GAIA-X[1] for governance, IDSA[2] for security and FIWARE[3] for collecting, managing and publishing context information, and allow identification of integration points with existing building data architectures such as MATRYCS, I-NERGY, BD4NRG etc. Figure 3 below illustrates the overall BUILDSPACE Conceptual Architecture structured in blocks to facilitate ease-of-understanding and enable consolidation of potential modifications and further enhancements that may emerge as the project advances. For the sake of clarity, the proposed Conceptual Architecture is broken down into three figures (Figure 4, Figure 5, Figure 6). The layers of information and their components have also been used as reference point for the BUILDSPACE platform's development. It should be highlighted here that the Conceptual Architecture, at its current version, has been configured following two extensive internal feedback rounds, where both the platform developer and the service providers were involved. The final version of the BUILDSPACE Conceptual Architecture along with the updates that were elicited from each internal feedback round, will be described in detail in Deliverable D2.3 which is due in M16 (May 2024).

[1] **Gaia-X** is an initiative that develops, based on European values, a digital governance that can be applied to any existing cloud/ edge technology stack to obtain transparency, controllability, portability and interoperability across data and services. (https://gaia-x.eu)

[2] **IDSA** provides organizations with practical guidance for implementing an identity-centric approach to security. (https://www.idsalliance.org/identity-defined-security-101/)

[3] **FIWARE** provides a mechanism to generate, collect, publish or query massive context information and use it for applications to react to their context. (https://www.fiware.org/2015/03/25/fiware-a-standard-open-platform-for-smart-cities/)

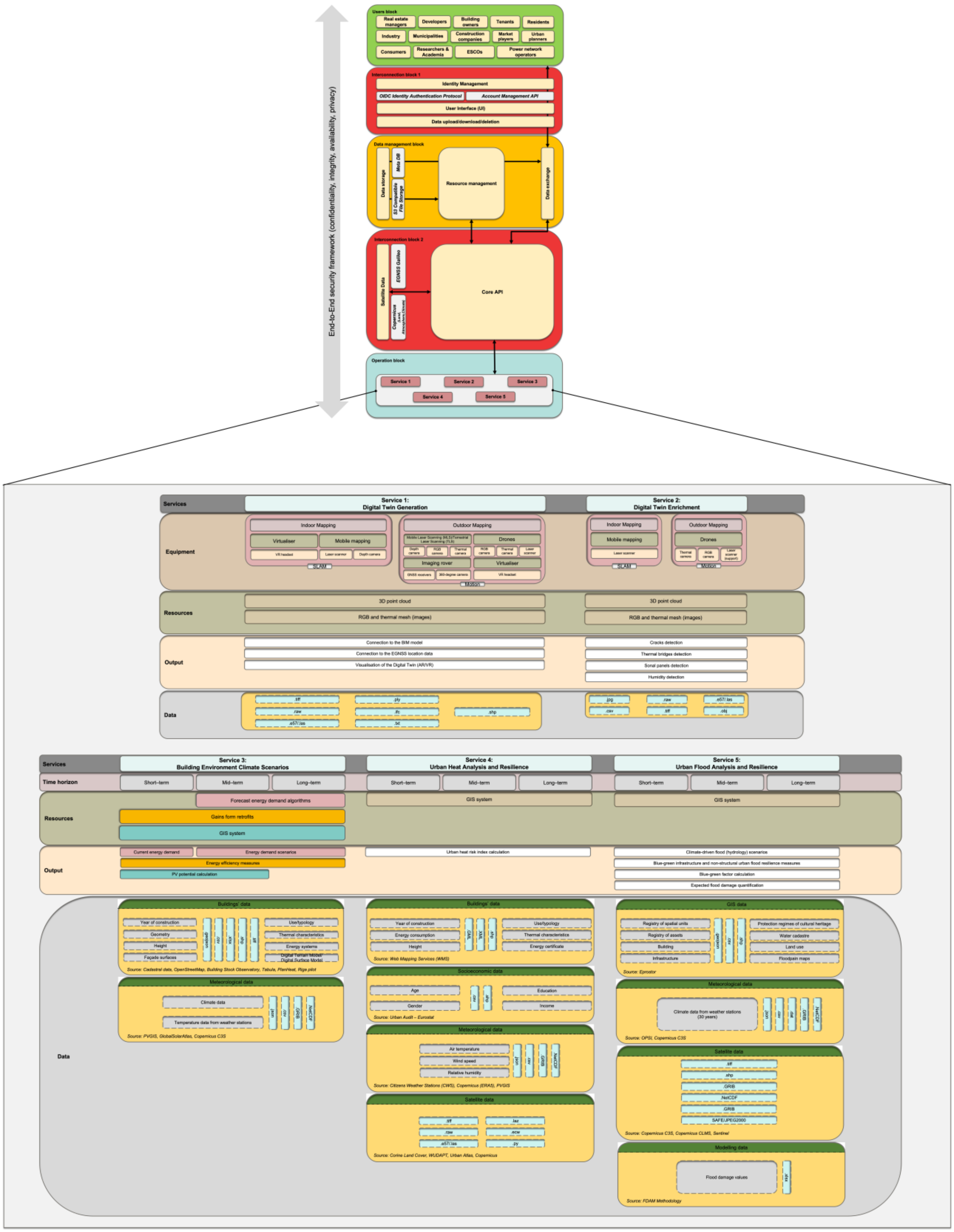


Figure 3. Overall presentation of the BUILDSPACE Conceptual Architecture

From a methodological point of view, drawing from Figure 3, it becomes clear that the Conceptual Architecture can be divided and read in two discrete parts. The first part is composed of five software blocks, which can be directly mapped to the different stages of the BUILDSPACE platform's development (Figure 4), whilst the second part is focused on diving into each service separately and providing key information on its functionality (Figure 5, Figure 6).

In this context, the blocks of the first part indicate a logical partition of the architecture (Figure 4), strictly representing the communication flows of the architecture implementation. As of this, the blocks are approached in a more software-oriented sense, and their inherent interconnection allows achieving a high-level functionality. The abovementioned blocks are the following:

- ***Users block:*** this block depicts the targeted end-users of the platform to be developed in alignment with the proposed Conceptual Architecture. These users have been presented in the deliverable D2.1, and are also mentioned here to facilitate the understanding of the end-to-end parts involved in a "data exchange" request. This request is presented as part of the "Data management block".
- ***Interconnection block 1:*** it constitutes the interconnection block between the platform and the end-user. It comprises of several layers that act as a centralised point for the users' experience in the platform. It serves as the middleware needed for acquiring, managing and exposing the data. At first, it includes the "identity management" layer that provides a secure and standardised method for users to log in with credentials of different types that are extended beyond just email and password, to enable future integration with EOSC and/or other identity federations/OIDC identity providers, allowing for the precise determination of user access to data according to the delegated access rights. On top of that, it ensures that a group of users sharing a common affiliation, also shares the same access privileges. Once the user is authorised, this specific block provisions for a User Interface (UI) which is used on the end-users' side as a means to upload/download/delete data from the platform at will. This data, as described below, will be associated to the respective user and stored in the platform on their behalf, enabling easy management to the same user upon entering the platform, or other users to request using this data through a "data exchange" request.
- ***Data management block:*** this block incorporates the "data storage", the "resource management" and the "data exchange" layers. The "data storage" is designed to ensure efficient and secure data management and is comprised of two sub-layers. By leveraging an S3-compatible file system, it lays out a scalable and versatile solution for actual file storage, allowing the end-users to access the uploaded data files that have been associated to them. Meanwhile, a metadata analysis that is employed to handle these files, offers flexibility in managing data exchange requests between the different groups of users. The architecture ensures a synchronised workflow between the file system and the storage database through a course of dynamic resource management actions.
- ***Interconnection block 2:*** it constitutes the interconnection block between the platform and the rest of the blocks. It mainly seeks to highlight the importance of a core API, that is utilised as the heart of the BUILDSPACE Conceptual Architecture (and of the consequent BUILDSPACE Core Platform), orchestrating the communication: a) between the platform (and the included services)

and a standalone user, b) between the different groups of users within the platform (and the included services), when for example a data exchange request is active, and c) between the platform (and the included services) and external satellite services such as Copernicus and EGNSS.

- ***Operation block:*** it includes all services that are hosted at the BUILDSPACE platform and are offered to the end-users for implementing complex location-based and remote sensing applications at either building or city level.

Transversally to all layers, an end-to-end security framework is applied, incorporating at all levels of the architecture, the needed security functionalities for confidentiality, integrity, availability, privacy and, in general, for cyber-attack prevention and mitigation.

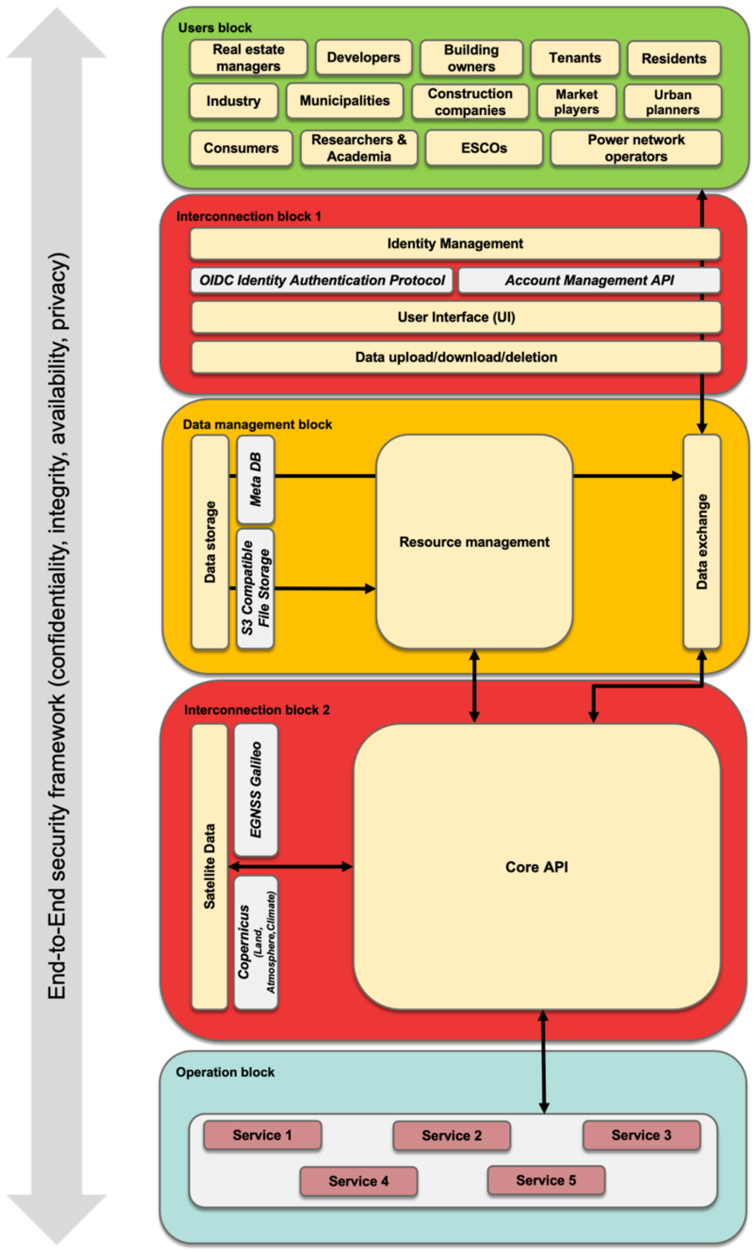


Figure 4. Presentation of the first part (software-oriented) of the BUILDSPACE Conceptual Architecture

Moving forward to the second part of the Conceptual Architecture (Figure 5, Figure 6), its goal is to depict the BUILDSPACE Services for: a) digital twin generation, b) digital twin enrichment, c) building environment climate scenarios, d) urban heat analysis and resilience, e) urban flood analysis and resilience. Following the same pattern as in the first part, the services' components have been identified and clustered in five distinct blocks, three of which are the same across all services (i.e., Resources, Output, Data), whilst two differ (i.e., Time horizon, Equipment). As a result of the latter, two groups of services are formed. To specify, the first two services (SE1, SE2) have been designed in such a way that the presence and use of equipment for indoor and outdoor mapping of a building is a prerequisite. As a result, the "Equipment" block can be found here. On the other hand, the remaining services (SE3, SE4, SE5) include the aspect of time horizon within their functional framework rather than any type of equipment, which led to the development of the "Time horizon" block.

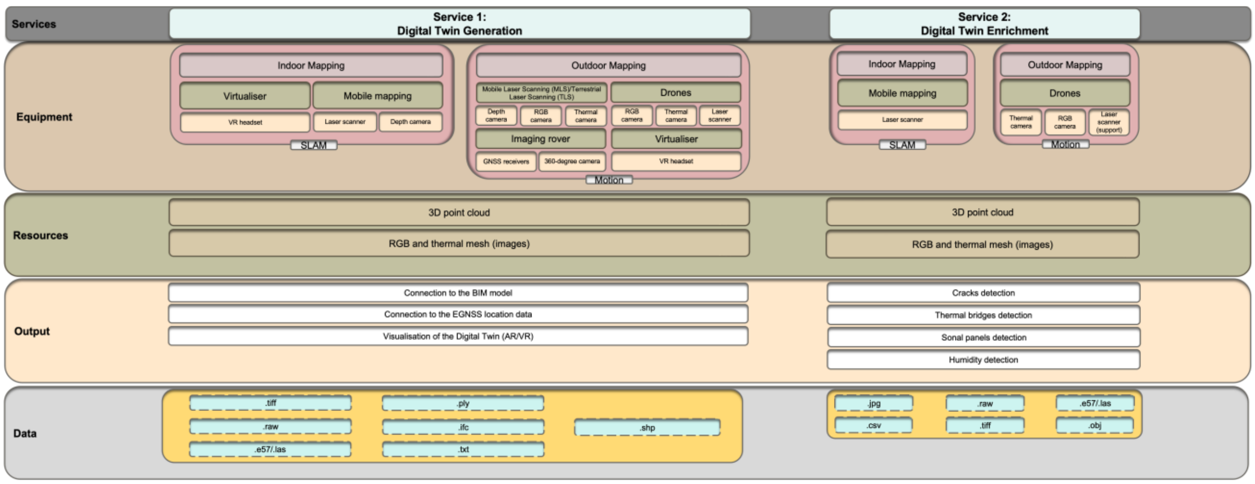


Figure 5. Presentation of the second part (software-oriented) of the Conceptual Architecture for SE1 and SE2

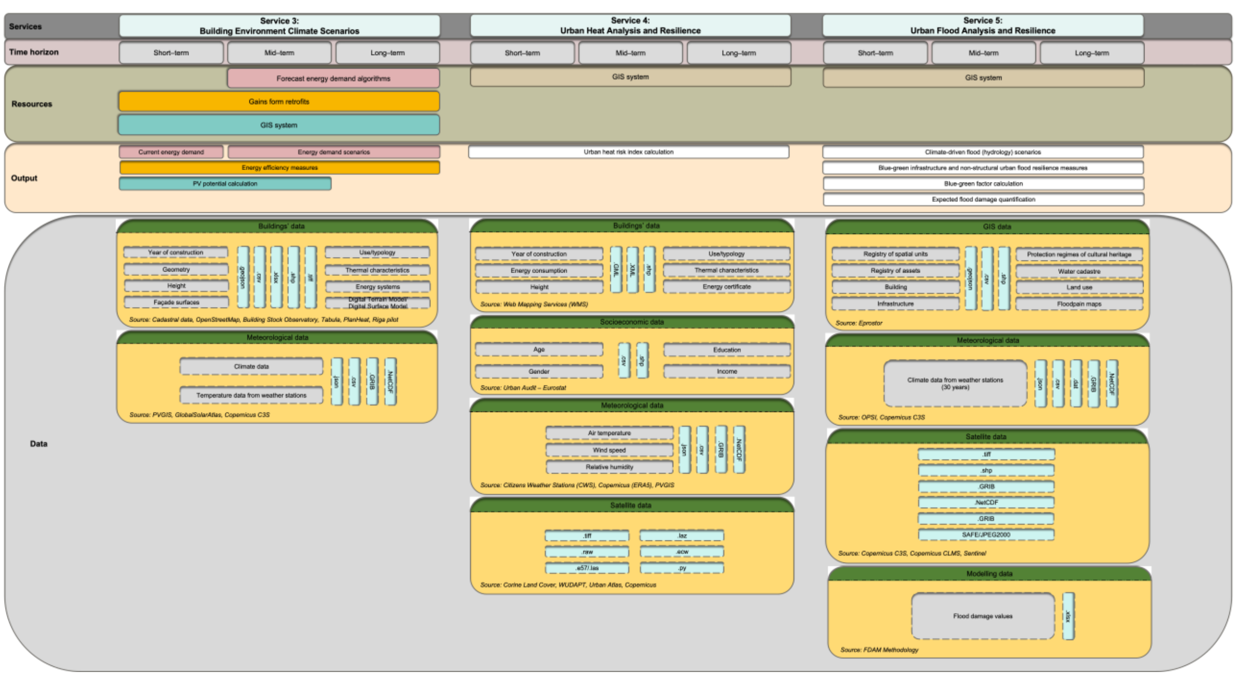


Figure 6. Presentation of the second part (software-oriented) of the Conceptual Architecture for SE3, SE4 and SE5

A brief description of each block's focal area is presented below. More detailed information on the included layers can be found in sections 3 to 6, where all services are technically analysed:

- ***Resources:*** this block presents the main tools that will be used within each service to provide the final output. In other words, resources include the "raw tools" to be employed in order to ensure that the anticipated output features are met.
- ***Output:*** this block presents the output of the services, in terms of highlighting their multiple uses for an end-user.
- ***Data:*** this block depicts the different types of data that are exploited within each service, along with their format for the sake of integrity. This is the data to be stored at the BUILDSPACE platform through the UI and transferred between users through data exchange requests, as mentioned above in the blocks of the Conceptual Architecture's first part.
- ***Time horizon:*** this block refers to SE3, SE4 and SE5. The reason behind this discrimination lies in the fact that the last three services involve future climate scenarios (e.g., SSP-RCPs, etc.), as of which, a direct mapping of each resource and output to a specific time horizon should be conducted.
- ***Equipment:*** this block involves only SE1 and SE2. Following up on the description of the "Time horizon" block, SE1 and SE2 require the use of equipment (e.g., drones, laser scanners, thermal cameras, etc.) towards providing the expected outputs, which is not the case for SE3, SE4 and SE5.

2.2. Core Platform Overview and Specifications

The design of the BUILDSPACE Core Platform follows a lean approach that addresses the complexities of contemporary data storage, exchange, and management. The Core Platform is designed to harmonize user authentication and group-based authorization, ensuring a secure and organization-centric approach to data storage, exchange, and management, but also to integrate various components seamlessly to ensure a robust, secure, and user-friendly experience. An in-depth visualization of the Core Platform is displayed in the following figure.

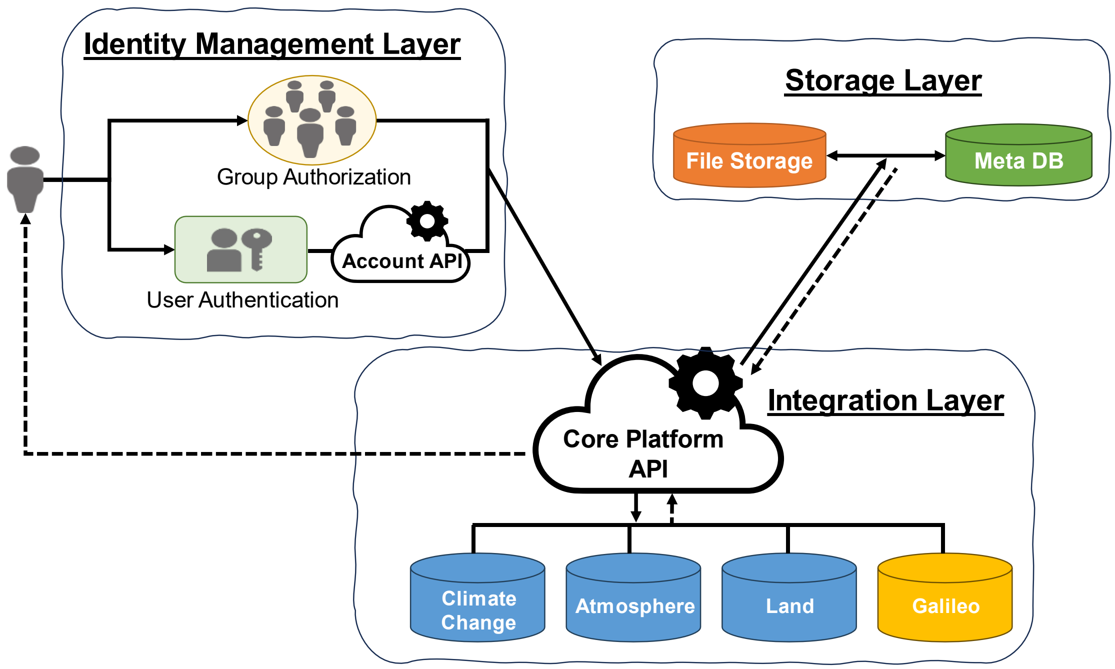


Figure 7. In-depth visualisation of the Core Platform's architecture

The primary objective is to provide a high-fidelity software solution that promotes trust in data storage, coupled with advanced access and sharing mechanisms—all encapsulated within a user-friendly experience. To achieve this, the Core Platform presents a REST API that serves as integrator between services and data, implementing also logic for managing files, folders, and sharing mechanisms, ensuring a cohesive and sophisticated user experience. The Core Platform follows a three-tier architecture with the following layers: i) identity management (part of the Interconnection block 1); ii) storage (part of the Data Management Block); and iii) integration (part of the Interconnection block 2).

2.2.1. Identity Management Layer

In the Identity Management Layer, the platform performs both user identification (User Authentication) and verification of the content that users are authorized to access (Group Authorization). This layer establishes a centralized point for user's identity management, allowing all services within the BUILDSPACE ecosystem to integrate. This integration will ensure that all services will leverage the robust authentication and authorization functionalities, promoting a consistent and secure user experience across the entire ecosystem.

User authentication is achieved through OpenID Connect (OIDC), providing a secure and standardized method for users to log in with their email and password. OIDC serves as a secure identity layer, extending OAuth 2.0 for standardized user authentication. Users can leverage existing credentials for secure access to different applications. OIDC issues identity tokens in JSON Web Token (JWT) format, ensuring the secure transmission of user information. In terms of deployment, the open-source free software, Keycloak, was selected.

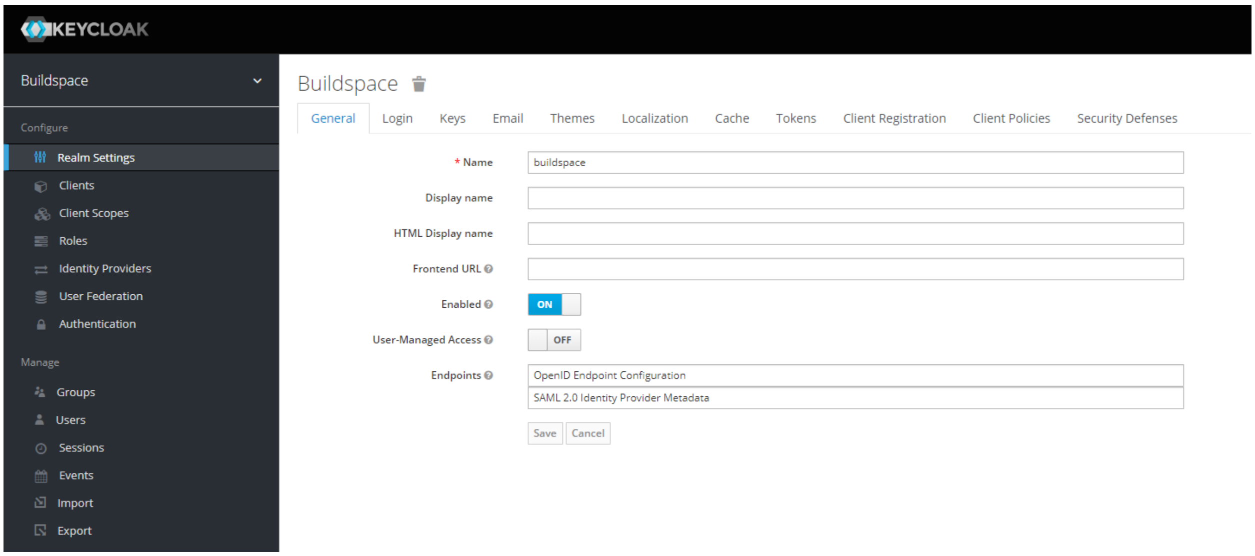


Figure 8. Implementation of Keycloak in the BUILDSPACE ecosystem

In general, OIDC protocol uses standardized scopes to clearly define access levels during authentication. Leveraging these scopes, the system integrates group-based authorization provided by OIDC, allowing for the precise determination of user access to data. Within an organization, users sharing a common group affiliation also share access privileges, streamlining data sharing among members of the same organization. The group functionality of Keycloak enhances the efficiency and precision of access control within collaborative environments.

A complementary component to Keycloak that serves as an administrative interface for organizational management was also implemented. Acting as an administrative gateway, a minimal yet powerful generic REpresentational State Transfer (REST) API, developed with OpenAPI standards in Python (v3.8.6), facilitates tasks such as creating new organizations, adding users, and managing credentials. The API is open-source and available at https://github.com/PROJECT-BUILDSPACE/account-manager-api, and the Swagger documentation at https://account-buildspace.euinno.eu/swagger/.

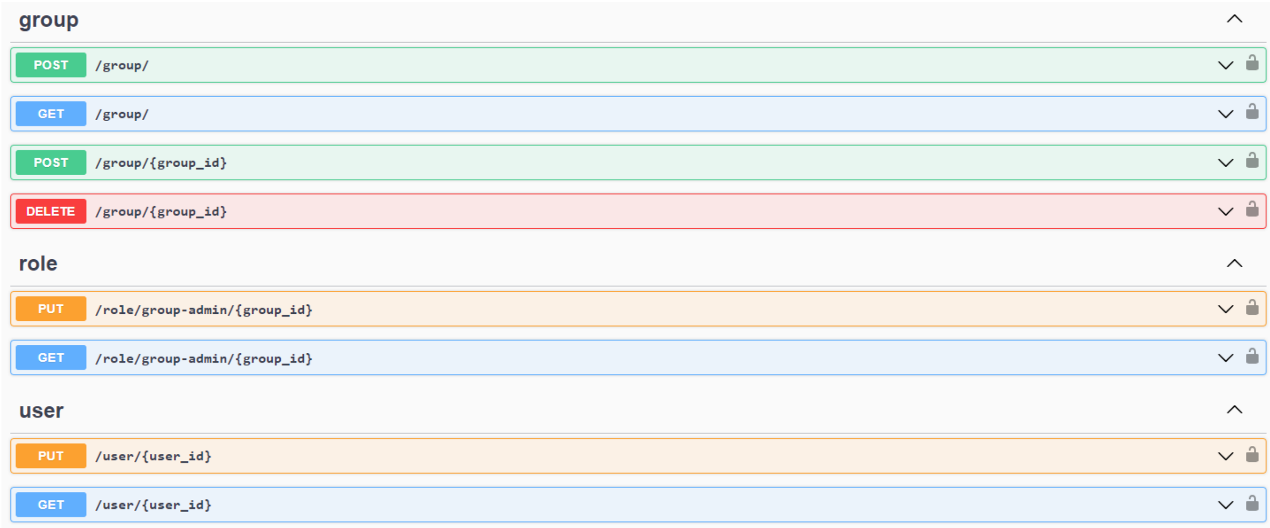


Figure 9. Swagger of the Accounts REST API

2.2.2. Storage Layer

The Storage Layer of the Core Platform is designed to ensure efficient and secure data management. Leveraging an S3-compatible file system, namely MinIO, it provides a scalable and versatile solution for actual file storage. Meanwhile, metadata associated with these files is stored in a NoSQL database (MongoDB), offering flexibility in handling diverse metadata structures. This implementation ensures a synchronized workflow between the file system and the metadata database. Both MinIO and MongoDB were deployed on the Core Platform cluster. More information, as well as the manifest files of the deployments, can be found in Section 2.3.2.

Serving as the primary repository, MinIO is integrated for efficient and agnostic data storage. MinIO is an open-source software that is built for high-performance object storage utilizing parallelization techniques and horizontal scalability by adding new nodes to the cluster. In addition, it provides various security features, including encryption in transit and at rest as well as the support of secure communication protocols. Its nature ensures scalability, reliability, and high availability, aligning with the platform's commitment to data integrity. Notably, the architecture prioritizes data privacy, with files stored as multiple parts, in an anonymized fashion to uphold confidentiality and security standards. In addition, this choice aligns with the platform's commitment to handling diverse data types efficiently.

Metadata storage is facilitated through MongoDB, providing a flexible and agile solution for storing metadata associated with the files. MongoDB’s schema-less approach accommodates various metadata structures efficiently, adapting to the evolving needs of the platform. In addition, the advanced query capabilities, coupled with the organization-centric approach, empower users to perform detailed searches based on metadata attributes.

2.2.3. Integration Layer

A REST API, that follows OpenAPI standards, serves as the backbone of the BUILDSPACE Core Platform, orchestrating seamless communication and interaction across a spectrum of essential functionalities. The API is developed in Golang (v1.20.3) and is open-source and available at https://github.com/PROJECT-BUILDSPACE/storage-api. Built upon a foundation of standardized HTTP requests as described in the API Swagger documentation, the API harmonizes the integration of critical components within our system. The swagger documentation of the full list of the Core API endpoints is available at https://api-buildspace.euinno.eu/swagger/ and is presented in the figure below.

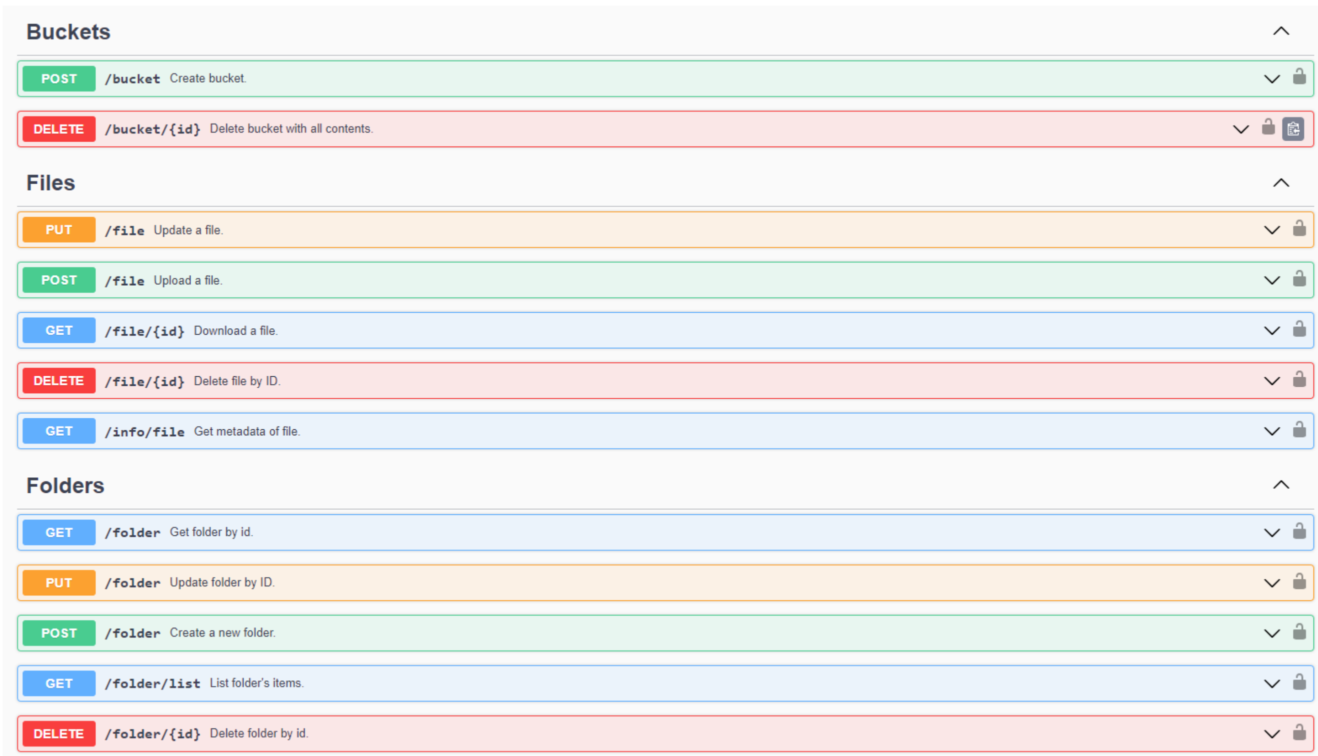


Figure 10. Swagger of the Core Platform's REST API

By receiving and processing HTTP requests, the Core API manages the Core Platform's operations. This includes facilitating the uploading/downloading/deleting of files, creating MinIO buckets, establishing folders for organized content, and executing operations such as folder creation, deletion, and sharing. The Core API interconnects with the Identity Management and Storage layers. This interconnection ensures a seamless flow of data, where files are stored with anonymity in MinIO, metadata is efficiently managed in MongoDB, and user access is authenticated and authorized through Keycloak.

Strict data models are meticulously designed and implemented to enhance interoperability. By adhering to well-defined and standardized data formats, a common language for data exchange has been established, ensuring consistency, reducing ambiguity, and promoting seamless communication between different components and services. This strategic approach not only facilitates the use of diverse systems within our project but also aligns with industry best practices for achieving interoperability, cross-platform compatibility, and long-term stability. The Swagger documentation for the Core API provides a visualization of the data models.

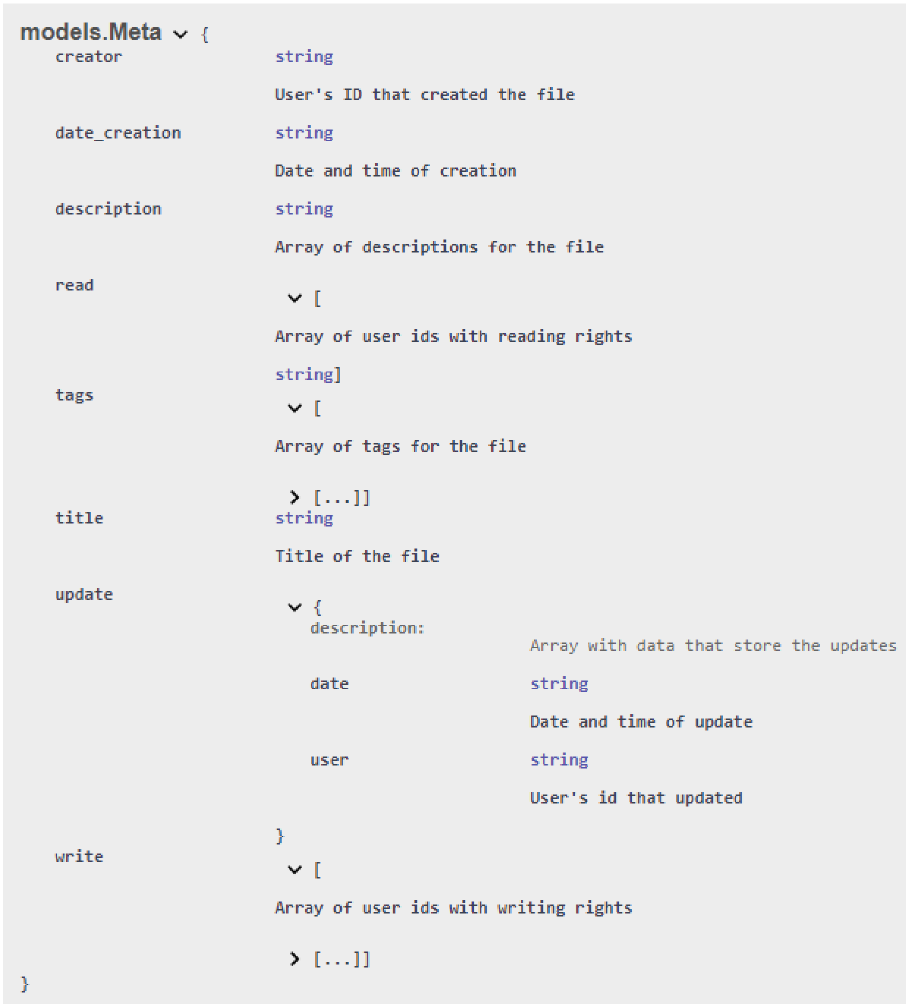


Figure 11. Example of the data model of the metadata stored in MongoDB

In addition, in the next iterations of the Core API, it will serve as the integrator of three Copernicus APIs related to the Land, Climate Change, and Atmosphere services. This integration will stand as a critical facet of our project, aimed at consolidating diverse datasets seamlessly. By merging information from these services, a unified and comprehensive data repository will be created that will enhance the BUILDSPACE ecosystem's capabilities. Also, the integration of the EGNSS Galileo service is planned, which will provide a comprehensive and unified gateway for accessing geospatial and environmental data.

In a nutshell, the REST API serves as a crucial intermediary for all services within the BUILDSPACE ecosystem, providing a standardized interface for data retrieval and manipulation. As the primary point of integration, it ensures that various services can efficiently consume and contribute to the shared data ecosystem, embodying a unified approach to data management and collaboration.

2.3. Core Platform Infrastructure

2.3.1. Runtime environment

In the infrastructure of the BUILDSPACE Core Platform, we have adopted Docker, a widely used containerization tool. Containerization, as established by Cito (2016), stands as a foundational technology that generates standardized software units. Its primary function is to encapsulate both code and its dependencies, ensuring the seamless and efficient execution of microservices across diverse computing environments. Docker's technology facilitated the creation of lightweight, self-contained Docker images, encompassing all essential components for running microservices, including code and configurations.

To make use of Docker containers within the BUILDSPACE Core Platform, the requisite software, Docker Desktop is available for free, while the Docker Engine (needed to run the containers) can be installed on various infrastructures, ranging from Virtual Machines (VMs) on servers to personal computers, and is compatible with most operating systems. On Windows, Docker can be effortlessly installed and run on VMs through a dedicated installer that addresses all necessary prerequisites. Docker also seamlessly operates on a broad spectrum of Linux distributions, such as Ubuntu, Debian, and on Apple computers. This versatile compatibility ensures that the developed software can be run on any infrastructure or personal computer, thereby maximizing its utility for stakeholders in both industry and regulatory authorities.

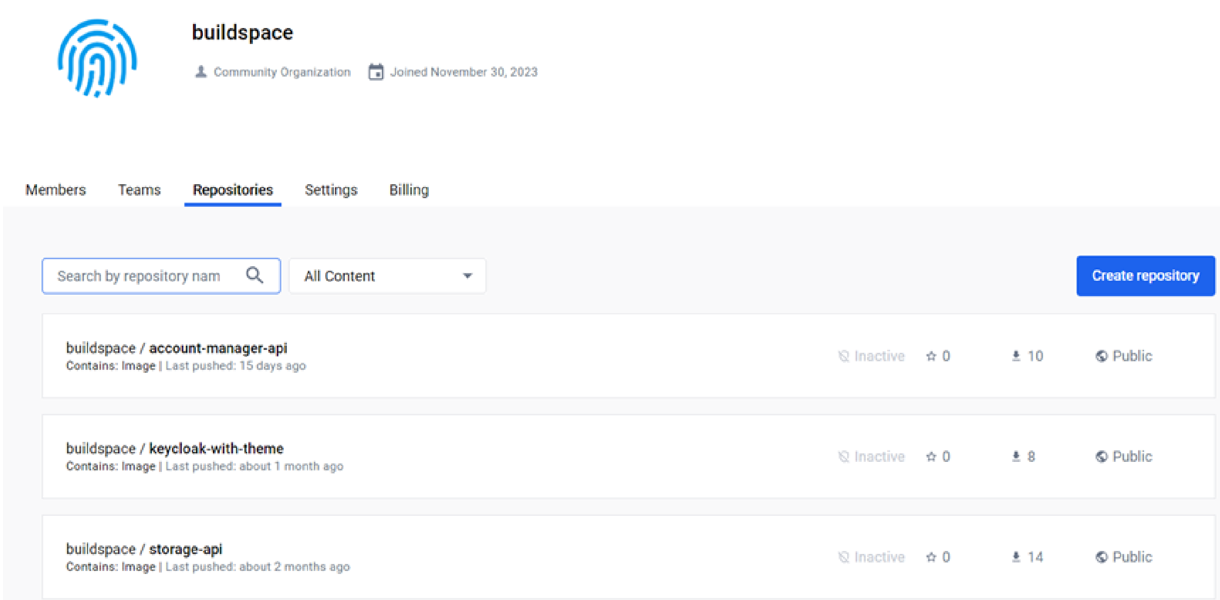


Figure 12. Docker repositories of the BUILDSPACE organization related to the BUILDSPACE Core Platform

2.3.2. Container orchestration through Kubernetes

Although containers operate independently, in many cases, multiple containers must work together. While managing each container separately works well for simple applications, it becomes cumbersome and error-prone in more complex systems. Deploying containers in virtual infrastructures, such as those provided by cloud computing providers, offers significant advantages, including increased cost-effectiveness and improved resilience. To streamline and automate deployment, scaling, and management of containerized applications, various ecosystems, collectively known as DevOps, have been developed.

To determine the most suitable solution for our project, we assessed leading ecosystems such as Docker Swarm, Kubernetes, and OpenShift. Currently, Kubernetes and OpenShift stand out as the most fitting for our requirements. Among these, Kubernetes was selected as the container orchestration software, due to its popularity and its cloud-agnostic nature, providing great flexibility in choosing hosting infrastructure.

In this section of the deliverable, we outline the present status of the BUILDSPACE Core Platform Kubernetes cluster, adhering to cloud-native development practices and enabling improved software management. The cluster is comprised of several collaborating components, including Deployments, Pods, Replica Sets, Services, and Ingresses. At their core, Kubernetes components are defined using configuration files written in the Yet Another Markup Language (YAML) data serialization language. All manifest files of the project are available at https://github.com/PROJECT-BUILDSPACE/kubernetes-manifests.

2.3.2.1. Core Platform Pods

A pod in Kubernetes is the fundamental unit of deployment, representing the smallest and simplest execution environment. It encapsulates at least one container, shared storage, and network resources, all of which are deployed together on a single host. A pod acts as a cohesive unit, fostering close collaboration between the containers it contains. This design enables efficient communication and resource sharing, making pods a fundamental building block for managing and scaling applications within a Kubernetes cluster. The current cluster contains 18 pods (a screenshot presenting 5 of them is shown in Figure 13).

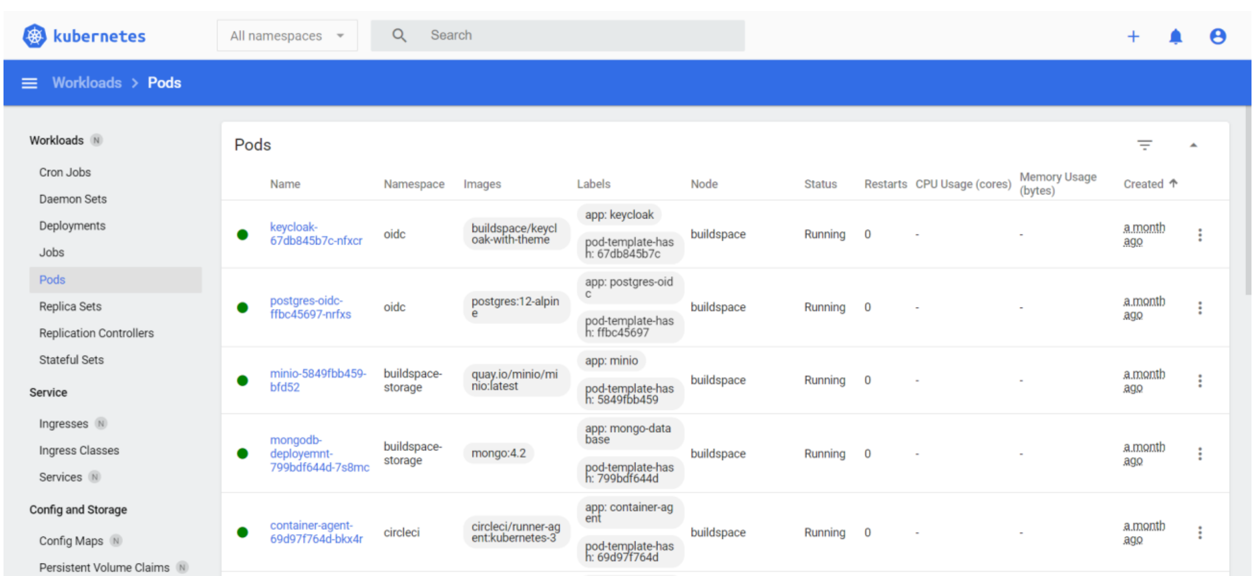


Figure 13. Screenshot displaying 5 pods of the BUILDSPACE Core Platform

2.3.2.2. Core Platform Deployments

A deployment in Kubernetes is a higher-level abstraction that facilitates the declarative management of pod replicas. It defines the desired state of the application, including the number of replicas to be running at any given time. Deployments enable seamless updates and rollbacks, making it easier to manage application changes without downtime. By defining the desired state, Kubernetes ensures that the actual state of the deployed pods aligns with the specified configuration, providing a robust and automated way to handle application deployments, scaling, and maintenance. The current cluster contains 11 deployments (a screenshot presenting 10 of them is shown in Figure 14). Table 2 presents the YAML file declaring the core platform's deployment in the cluster.

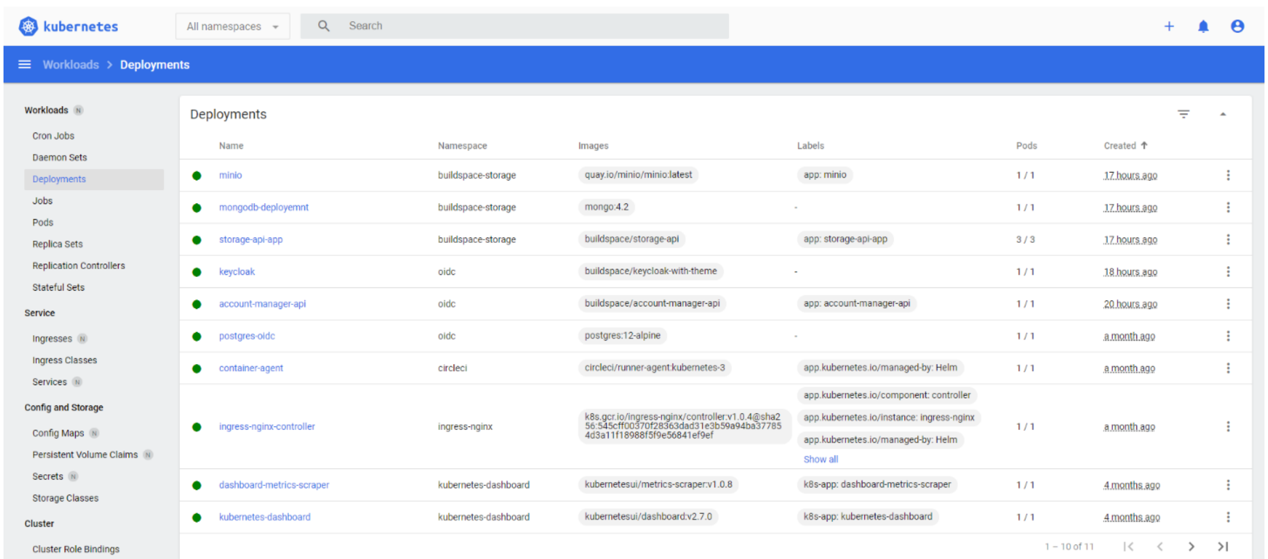


Figure 14. Screenshot displaying 10 deployments of the BUILDSPACE Core Platform

Table 2. YAML file declaring the BUILDSPACE Core Platform API deployment

```yaml
apiVersion: apps/v1
kind: Deployment
metadata:
  name: storage-api-app
  namespace: buildspace-storage
  labels:
    app: storage-api-app
spec:
  replicas: 3
  template:
    metadata:
      name: storage-api-app
      labels:
        app: storage-api-app
    spec:
      containers:
        - name: storage-api
          image: buildspace/storage-api
          ports:
            - containerPort: 8006
          env:
          - name: ACCESS_KEY
            valueFrom:
              secretKeyRef:
                name: minio-keys
                key: accessKey
          - name: SECRET_ACCESS_KEY
            valueFrom:
              secretKeyRef:
                name: minio-keys
                key: secretAccessKey
          - name: DATABASE
            value: minio
          - name: MONGO_URL
            value: mongodb://mongodb-service.buildspace-storage:27017
          - name: MINIO_URL
            value: minio.buildspace-storage:9000
          - name: OIDC_PROVIDER
            value: https://keycloak-buildspace.euinno.eu/auth/realms/buildspace
          - name: CLIENT_ID
            valueFrom:
              secretKeyRef:
                name: minio-client
                key: id
          - name: CLIENT_SECRET
            valueFrom:
              secretKeyRef:
                name: minio-client
                key: password
        restartPolicy: Always
  selector:
    matchLabels:
      app: storage-api-app
```

2.3.2.3. Core Platform Services

In Kubernetes, a service is a crucial abstraction that provides a stable endpoint for accessing a set of pods. It acts as a consistent and reliable entry point, enabling communication between different parts of an application or between applications within the cluster. Services abstract away the underlying complexity of managing individual pod IPs and provide load balancing capabilities, allowing for seamless discovery and connectivity. By defining services, Kubernetes facilitates a dynamic and scalable networking environment, promoting efficient communication and collaboration among various components of a distributed application. The current cluster contains 12 services (a screenshot presenting 5 of them is shown in Figure 15). Table 3 presents the YAML file declaring the core platform's service in the cluster.

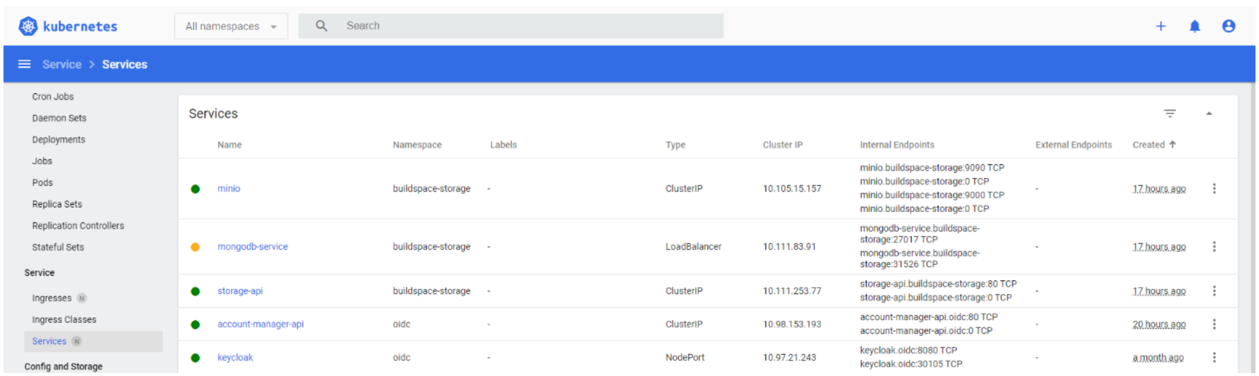


Figure 15. Screenshot displaying 5 services of the BUILDSPACE Core Platform

Table 3. YAML file declaring the BUILDSPACE Core Platform API service

```yaml
kind: Service
apiVersion: v1
metadata:
  name: storage-api
  namespace: buildspace-storage
spec:
  selector:
    app: storage-api-app
  ports:
  - protocol: TCP
    port: 80
    targetPort: 30000
```

2.3.2.4. Core Platform Ingresses

In Kubernetes, an Ingress is a powerful resource that serves as an entry point for external traffic into the cluster. It allows for the definition of rules and configurations to route requests to specific services based on paths, domain names, or other HTTP attributes. Essentially, Ingress acts as a traffic manager, providing a way to expose services to the outside world while offering flexibility and control over how different endpoints are accessed. By leveraging Ingress, Kubernetes enables the implementation of complex routing and load balancing strategies, enhancing the accessibility and reliability of applications deployed in the cluster. The current cluster contains 5 ingresses (a screenshot presenting them is shown in Figure 16). Table 4 presents the YAML file declaring the core platform's ingress in the cluster.

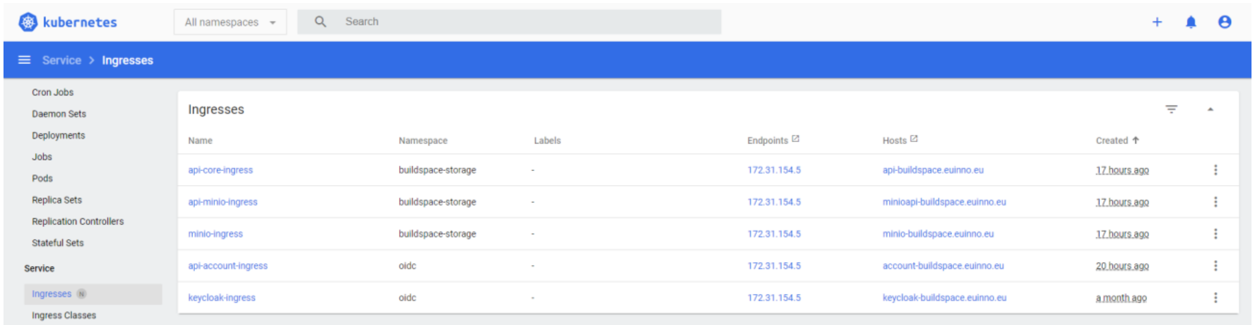


Figure 16. Screenshot displaying the ingresses of the BUILDSPACE Core Platform

Table 4. YAML file declaring the BUILDSPACE Core Platform API ingress

```yaml
apiVersion: networking.k8s.io/v1
kind: Ingress
metadata:
  name: api-core-ingress
  namespace: buildspace-storage
  annotations:
    kubernetes.io/ingress.class: nginx
    nginx.org/client-max-body-size: "10m"
    nginx.ingress.kubernetes.io/proxy-body-size: "10m"
spec:
  rules:
  - host: api-buildspace.euinno.eu
    http:
      paths:
      - path: /
        pathType: Prefix
        backend:
          service:
            name: storage-api
            port:
              number: 80
```

3. BUILDSPACE services at building scale: Digital Twin Generation and Enrichment

The Digital Twin generation (SE1) aims to reconstruct the geometry of the digital twins of buildings from locally sourced geometry data and will build the associated interfaces for human-information interaction between users and Digital Twins in mixed reality environments. The service will integrate methods to detect and classify building elements and convert it into a high-compatibility format digital model. The result of the digital twin will be exhibited in the XR (extended reality) support interface to enable the users to experience the building asset through the virtual environment.

The Digital Twin Enrichment (SE2) has as its main objective to provide additional information to the platform at the scale of the building. This information will be based on RGB and thermal images using UAVs for the external envelope and SLAM-based point clouds for the internal envelope. The final objective of the provided information will be the identification and analysis of areas with thermal alterations in the building envelope (critical areas and envelope quality) and the supervision and detection of malfunctioning cells in rooftop solar installations; both processes will be carried out using artificial intelligence. This makes it possible to prioritise the areas if of a building that need intervention, in addition to having greater knowledge about the quality of the envelopes in buildings to be rehabilitated. For newly constructed buildings, it allows to observe the differences with the proposed design and evaluate the errors made in the construction of the thermal envelope.

SE1 and SE2 also include the calculation of the proposed KPIs. First, the percentage of façade that is obstructed by obstacles when capturing drone images, which is calculated by generating a ratio between the captured envelope and the actual envelope; secondly, the quality of the point cloud, calculating the density of the point cloud by measuring the distance between points; and, finally, the noise on the point cloud surfaces, calculating the similarity between the elements obtained with respect to the real ones.

Deliverable 2.2 "Use cases and design of applications' dashboards" reported three technical use cases related to SE1 and SE2:

- **UC1.1 – gDT generation with EGNSS data integrated**. The objective of this use case is to create geometric digital twin models for the four pilot projects based on the scanned data of the physical twins of buildings. The generated DT model will be coordinated with the EGNSS data to be potentially integrated with the city level digital maps or 3D models. The results of the DT will be shown in the VR/AR platform to realise comprehensive visualisation and interaction with the users. The multiple 3D digital models of one building will be shown at one solution, including the IFC model, LiDAR or Image point cloud models.
- **UC2.1 – Mostostal quality control of a new building**. The aim of this scenario is to test the feasibility of controlling a building, focusing on the identification of anomalies in the envelope, in particular thermal bridges. The building's Digital Twin will be enhanced with a functionality that uses thermal scan data to identify and categorize thermal bridges, and the generation of a thermal bridge report will be enabled. In addition, thermal scanning will be used to monitor the control of solar panel cells.

- **UC2.2 – Intervention areas of a municipal building in Piraeus**. The objective of this scenario is to identify areas of intervention in a municipal building, focusing on the identification of anomalies in the envelope, especially thermal bridges. The building's Digital Twin will be enhanced with a functionality that uses thermal scan data to identify and categorize critical areas, and the generation of a critical area report will be enabled.

3.1. Input and Output

The input for constructing the digital twin is the LiDAR or image point cloud data collected from the building scanning workflow. The data might be collected via the approaches of Airborne Laser Scanning, Terrestrial Laser Scanning, mobile scanning, and drone fly. The final input of SE1 should be the registered point cloud model of the overall building. The accuracy and scope of the created digital twin are largely influenced by the scanned scope, density, and quality of the collected point cloud data. The point cloud processing algorithm will be developed to complete the point cloud detection and classification mesh generation and geometric digital twin creation. The output of SE1 will be the AR/VR supported interface with the generated gDT to support the city-level energy management in the further development. In the current document, i.e. Deliverable 3.1, the output of SE1 first focuses on the testing of the algorithm of the point cloud data processing of various building elements based on the collected pilot project data. The primary building structures like walls, openings and roofs are the main elements to consider at this stage.

Enrichment of the outer envelope requires a set of images (RGB and thermal images) as well as topographic points (in the form of GPS coordinates or total station coordinates). These inputs allow 3D point clouds of the outer envelope to be obtained using photogrammetric approaches. Additionally, it is highly recommended to have some on-site temperature readings to corroborate the data obtained by thermography with the real ones. For the interior envelope, the use of SLAM-based approaches equipped with RGB cameras is recommended. Between the interior and exterior envelopes, it is needed to have an overlapping area. This is necessary to place both 3D point clouds in the same coordinate system.

The output of the Service 2 is a 3D point cloud of the building, which includes geometric information, RGB colour, and thermal (exterior) data. This point cloud is in an interoperable *.e57* or similar format so that it can be integrated with the DT platform. On the other hand, the analysis of the envelope generated by artificial intelligence with the possible export of reports. On the other hand, in the enrichment of the model, the analysis of thermal and RGB images is developed with the help of artificial intelligence for the evaluation of the quality of the envelope, which are: detection of dampness, detection of cracks, detection of thermal bridges and their classification and detection of malfunctioning solar panels; all detections will have downloadable report documents.

Both services will be tested in the project pilots. All the four pilot cases will be tested in SE1, and among that, pilot 1 and pilot 3 will be tested in SE2 as well. To ensure the smooth delivery of both services, we completed the documentation for the pilot teams to select the appropriate buildings (see **section 9 with Annex A**). Furthermore, the technical specification is also provided supporting the teams to collect the high-quality scanned data for the further SE1 and SE2 development (see **section 10 with Annex B**).

3.2. Service Workflow

SE1 and SE2 are part of Task 3.2. Specifically, SE1 within T3.2.1 “Digital Twin generation”, and SE2 within T3.2.2 “Digital Twin enrichment”.

The designed technical pipeline is shown in Figure 17.

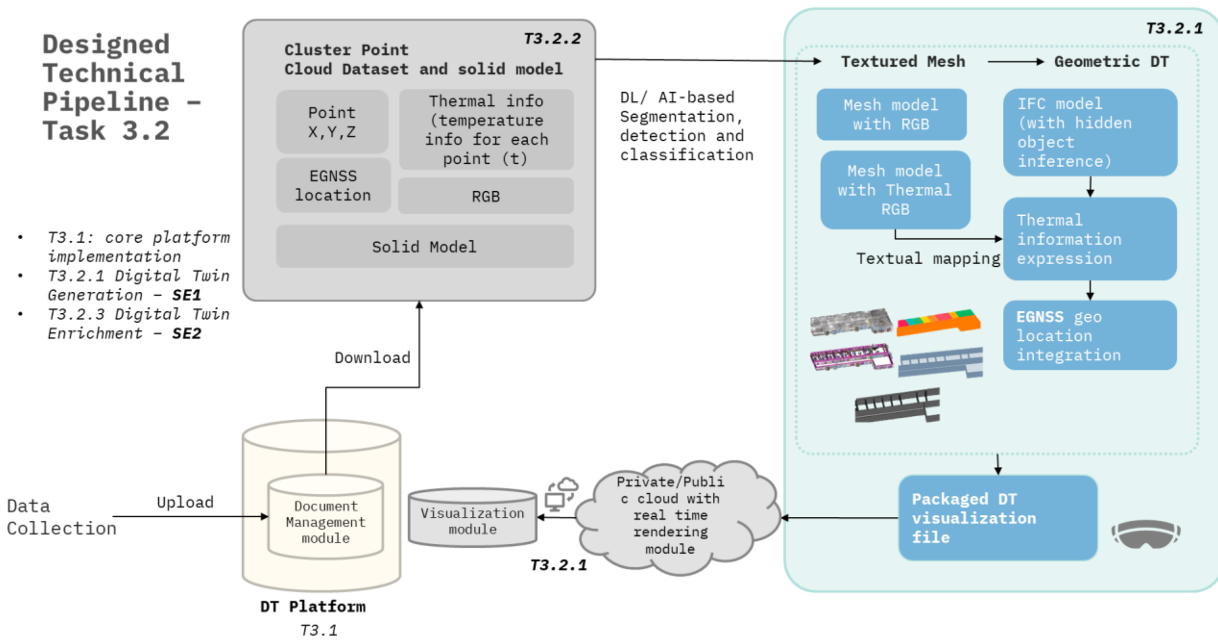


Figure 17. Diagram for the designed technical pipeline for Task 3.2 (SE1 & SE2)

There are three main parts in the SE1 (Task 3.2.1), which are the point cloud processing and geometry digital twin generation and the visualisation module of the digital twin. This deliverable focuses on the point cloud processing, and the conceptual framework development for the other modules of the service. In the point cloud processing module, a state of research deep learning supported algorithm is used to generate the mesh for the next step digital twin generation. In the digital twin generation module, the topology of the building elements is established for the hidden object inference. In the visualisation module, the EGNSS and required Copernicus Services data will be integrated in a web-based interface to allow users intuitively experience the created digital information in the virtual environment.

For the SE2, the main objective of the service is to support urban stakeholders (urban and energy planners, real estate developers, policy makers, etc.) and citizens (homeowners, residents, etc.) in knowing the thermal conditions of their building envelopes, being able to prioritize the areas of intervention and assessing the severity through a report.

The information calculated for this service will be displayed in a digital twin (georeferenced) of the building with its immediate surroundings as a visual medium, providing different layers of information through which to draw conclusions.

In the digital twin, the user can navigate the building through the platform, using augmented reality or virtual reality, touring its spaces and visualizing the results in detail. In addition, you can enable or deactivate layers of information (model, RGB image, thermal image) to compare or draw conclusions of your own. On the other hand, a final layer of results will be provided with the areas of intervention or critical areas in the envelope with a report analysing the type of area.

Figure 18 shows the complete workflow of the services, with the different functionalities that will be offered to the user.

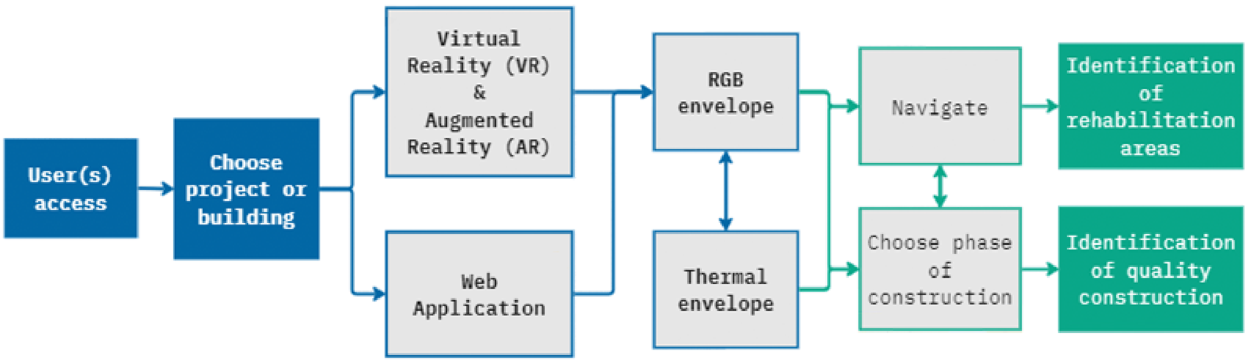


Figure 18. Services 1 and 2 workflow diagram

First, the user accesses the service via the central BUILDSPACE platform. Next, a map will be shown with the different cities with digital twin development. The user can choose one of them to access the building or project.

The user can then select the platform's display mode: Augmented Reality and Virtual Reality or in the web app. The functionality of both is the same, but the medium by which it is displayed is different. In both situations, the user will observe the digital twin, a 3D model with the possibility of adding different types of information.

Having selected a display mode, the building will open with the display of the RGB image layer as the default layer, from there it can be removed or changed to thermal image display.

Depending on the project the user has selected, they can simply browse and analyse each layer or choose different phases of the construction to compare them and see the progress made on the site. In this phase, the user will still be able to change the display image between model, RGB or thermal.

Finally, the user can activate a layer with the results, which depending on the building (building to be rehabilitated or under construction) will allow to observe the critical areas or the quality of construction. Both will be represented in a similar way, detecting areas of humidity, thermal bridges, malfunctioning solar panels, etc. These areas will have a report attached, identifying the areas, and giving as much information as possible for the understanding of the scenario.

3.3. Application of the services and current progress

3.3.1. Service 1 – Geometric Digital Twin Generation

Service 1 is being developed in all the pilot projects. Currently, only the point cloud data of pilot 2 – RPR are collected. In this case, only the envelop of this building is scanned and the key elements for the geometric digital twin generated is the roof, wall, windows and doors. The collected point cloud data shows all the façades and roof of the buildings in high quality. It was the main building of Riga Technical University since 1958 until 2021. The point cloud data (see Figure 19) of this target building is the segmented part of the city level scanning, conducted by the terrestrial laser scanner (Leica RTC360 3D Laser Scanner) and the Riegl airborne scanner. It is an architecture most closely resembles a form of Renaissance architecture inspired by the classical Roman style, which is characterized by its symmetry, proportion, and geometry.

The testing work of mesh generation on walls, windows and roofs are undergoing. The results show that around 90% of the area of the walls and windows can be detected, and they will be further converted to *.ifc* format. The condition of the roof in this case is complex and it involves multiple primitive type of roofs in the general roof databases. To this aim, training work is ongoing to automatically model the complex roof in this pilot case. Furthermore, the shape, topology and semantic relationship of the building elements are being reviewed to develop an ontology of the building element for supporting the hidden object inference. This work is planned to be reported in the next deliverable 3.2.

In the BUILDSPACE Project, SE1 will be implemented and tested across the four pilot cases. These cases span a range of architectural styles, from contemporary designs to those traditional architectural style. The development of the point cloud processing algorithm—encompassing segmentation and classification—relies primarily on the machine learning training dataset. By applying SE1 across these diverse pilot projects, the training dataset will encompass a variety of styles, thereby enhancing the core algorithm's potential for replication.

Figure 19. Pilot 2 Point Cloud Data

The definition of level of details (LOD) is significant of the constructed geometric digital twin. The improved series of 16 LODs is proposed by Biljecki et al. (2016), which offer a more precise specification of the exterior geometry of buildings. This new specification aims to reduce modelling freedom and provide clearer guidelines to produce 3D city models. It includes two hybrid models that reflect common acquisition practices, ensuring that the new LODs are compatible with existing CityGML 2.0 LODs while being format-agnostic. For the digital twin construction, the output of the geometric digital twin will be range of LOD2.1 to LOD3.2 take Figure 19 as a reference.

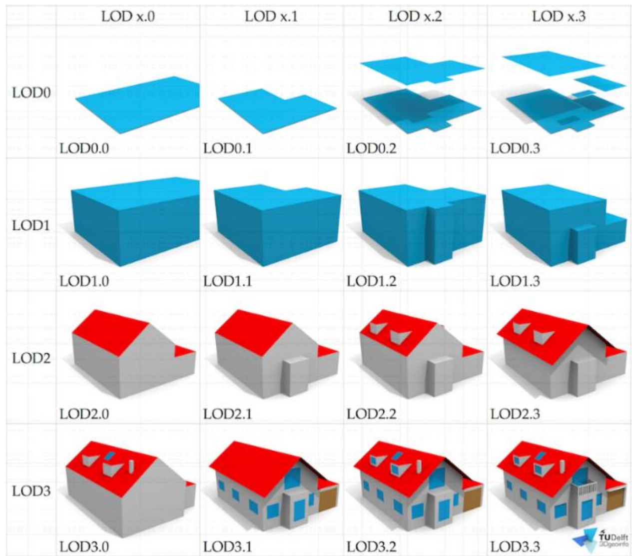


Figure 20. LOD specification for 3D building models Biljecki et al. (2016)

3.3.1.1. gDT generation of building indoor environment

The construction of building indoor environment will be conducted in the scenario 1 of pilot 1 (MOS) pilot case. The building elements that will be constructed in the indoor geometric digital twin is the walls, ceilings, floors, windows, and doors. After collecting raw point cloud data from indoor laser scanning, the initial step involves data transferring and cleaning. After the noise removal, the point cloud registration is conducted, where multiple scans are aligned and integrated into a unified coordinate system through processes like pre-alignment and fine alignment, using techniques like the Iterative Closest Point (ICP). This alignment is mainly designed to check the accuracy to ensure a coherent representation of the indoor environment. After the data registration, the point cloud data will be further cleaned to remove residual noise and is normalized to ensure consistency, preparing it for feature extraction. This stage is pivotal for the next steps of segmentation and classification. This seamless flow from raw data collection through to the preparation stage sets a strong foundation for accurate segmentation and classification to pave the way of gDT generation.

For the primary structural objects in the indoor environment, for example the walls, ceilings and floors, the planar/cylindrical surface detection method, such as RANSAC, Hough Transform, or region-growing algorithms are always being implemented. And it is a challenging task to detect the windows, and doors in the digital twin construction process. In this task, the indoor environment point cloud model will be tested based on the solutions developed by our team. The detection of wall, ceilings, and floors will be conducted based on the voxel-growing method (Pan et al., 2021). Besides, the two-step method of object detection will be implemented for the construction of windows and doors (Drobnyi et al., 2023). The two pipelines will be improved and integrated to deliver a geometric indoor digital twin.

Based on the methods mentioned previously, the point cloud clusters with the specific labels will be segmented and classified. The point cloud clusters will then be converted to 3D model with *.obj* format. In the final step, a self-developed PyTorch-driven method will be conducted to generate the *.ifc* files from *.obj* files. Initially, the script imports necessary libraries such as *numpy* for numerical operations, *ifcopenshell* for handling IFC files, *pywavefront* for reading *.obj* files, and *uuid* for generating unique identifiers. It sets up a new blank IFC file by copying essential elements from a blueprint IFC file, including project details and geometric representation context, ensuring that the new IFC file has a proper structure and metadata.

The core of the process involves loading the *.obj* file to access its mesh data, including vertices and faces. This data is then adapted to fit the IFC format's expectations, such as adjusting face indices to accommodate IFC's zero-indexing. A new IFC file is created, and the mesh from the *.obj* file is meticulously converted into an IFC-compatible format, including defining a unique identifier for each element, creating a 3D point list for vertices, and transforming mesh faces into IFC's polygonal face set. Besides, the solution also handles the spatial placement and orientation of the mesh within the IFC file, ensuring it is correctly positioned and oriented. Finally, the mesh is integrated into the building's structure by assigning it to a specific storey and setting up the necessary relationships within the IFC file's spatial structure.

3.3.1.2. gDT generation of façade

The main task of façade construction is the detection of building external wall and the windows and building entrance. Currently, the detection of façade wall and windows has been tested in the Pilot project 3 – RPR (Riga Planning Region) case. The workflow is shown in Figure 21. The results should that it can identify the external walls and windows accurately (refer to the Figure 22 and Figure 23). The algorithm used in this step is also developed by our team and the research work is not yet published.

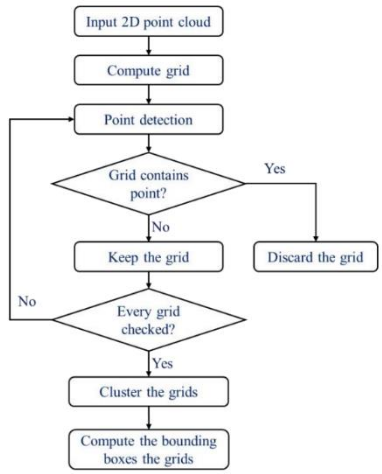


Figure 21. Pipeline of wall and window detection

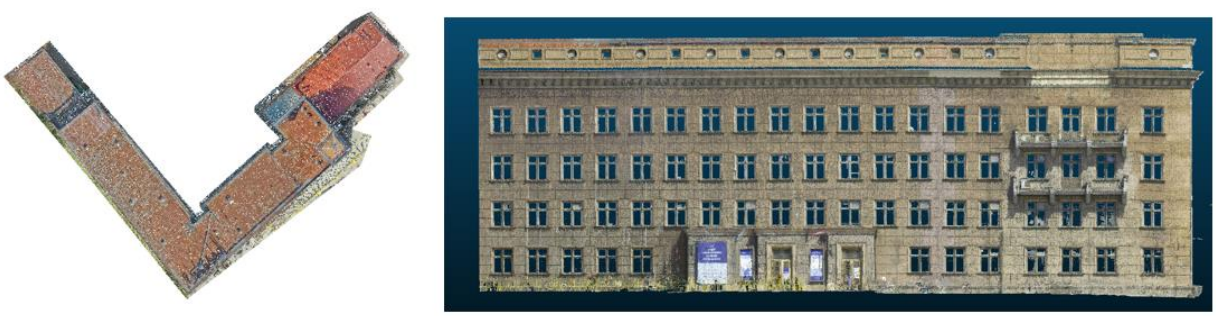


Figure 22. Facade extraction of Pilot project 3

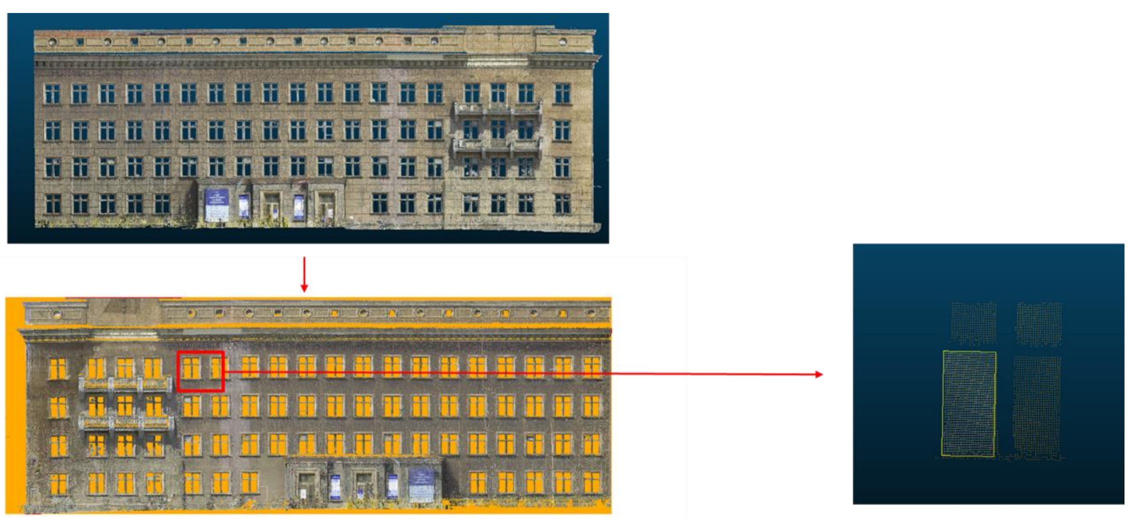


Figure 23. Detection of windows in the external wall and boundary extraction of one window

In this method, the negative parts in the point cloud are detected and to be recognised as the windows with the specific threshold. The solution uses the Point Cloud Library (PCL) and the Computational Geometry Algorithms Library (CGAL) for processing 3D point clouds and performing geometric operations.

The code is structured into several main functions, each designed for different tasks such as window detection, facade extraction, and finding the minimum polygon.

The solution includes three parts, which are PCL operations, CGAL operations, and specific object extraction. PCL operations involve reading, pre-processing (such as down-sampling, and noise filtering), segmenting, and projecting 3D point cloud data to identify and analyse geometric features or objects within the data, using robust methods like RANSAC for plane fitting and k-d trees for efficient spatial searches. In the CGAL operations, it provides advanced geometric algorithms to perform precise computations on 2D projections of 3D data, such as generating convex hulls, computing minimum enclosing rectangles, and other polygon operations, enabling detailed analysis of shapes and structures. The last step is the object identification based on the specific object functionalities. It leverages PCL for initial 3D point cloud processing and CGAL for detailed geometric analysis, focusing on identifying architectural features and optimizing geometric representations for various applications.

3.3.1.3. gDT generation of roof

The construction of roof is based on the method of 'point2roof' (Li et al., 2022). It is an innovative method of roof model rebuild based on the ML-driven for vertex detection and edge predication. This method has been verified that can be used in the pilot project 3 – RPR (the segmented part of results is shown in Figure 24). However, more training datasets are needed in this scenario to make the results more solid. The technical pipeline is shown in the Figure 25.

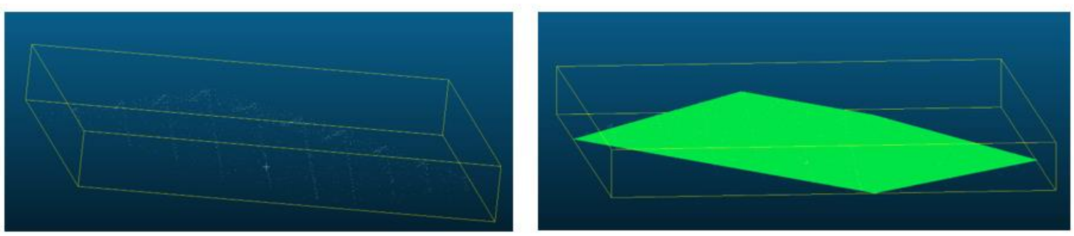


Figure 24. Test segmentation of roof construction (left: point cloud data for roof and right: 3D mesh)

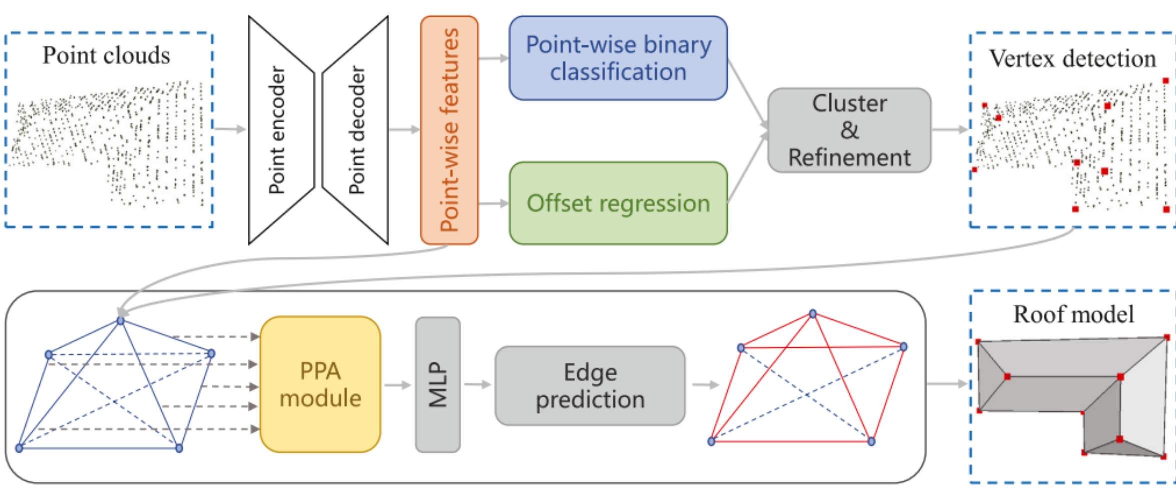


Figure 25. Technical pipeline for the roof construction (Li et al., 2022)

This innovative method for roof model reconstruction employs a machine learning (ML)-driven approach, focusing on the detection of vertices and prediction of edges within point cloud data. At its core, it utilizes a combination of convolutional and linear layers for feature extraction, where convolutional layers (Conv2ds, Conv1ds) capture spatial hierarchies and patterns, and linear layers (Linears) abstract these features further, all enhanced with batch normalization for improved training dynamics. This setup is adept at processing the complex spatial data represented in point clouds, extracting meaningful patterns and structures essential for identifying roof vertices and edges.

In addition, the method incorporates the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm, implemented as a PyTorch function within the *DBSCANCluster* class, to cluster point cloud data effectively. This unsupervised clustering technique is particularly suited for point cloud data, enabling the identification of distinct structures or objects by grouping closely packed points while distinguishing outliers. The *GetClusterPts* class is used to further refine this process by extracting crucial points and their quantities within each cluster, providing insights into the structural composition of the roofs.

To facilitate continuous improvement and application of the model, utility functions like *load_params_with_optimizer* and *load_params* are included for managing model and optimizer states. This allows for efficient training resumption from checkpoints or leveraging pre-trained models, ensuring adaptability and scalability of the roof reconstruction process. Overall, this ML-driven method represents a sophisticated approach to reconstructing roof models from point cloud data, combining advanced feature extraction techniques with robust clustering algorithms to accurately identify and predict roof vertices and edges.

3.3.1.4. gDT for construction phase

The solution in the construction phase is designed for the scenario 2 in the Pilot Case 1 – MOS. The comparison of scanned point cloud models with IFC models, incorporating a time dimension, involves a technical pipeline designed to assess the congruence between the current physical state of a construction project and its planned digital blueprint (see Figure 26). The solution will be developed based on the method from the project **BIM2TWIN**.

It begins by overlaying the point cloud model, derived from laser scans or photogrammetry of the construction site, directly onto the corresponding IFC model, which represents the architectural and engineering intent in a structured digital format. To facilitate a detailed comparison, boundary boxes are generated for each object or component within the IFC model, serving as defined spatial regions for analysis. The point cloud data is then examined to count the number of points falling within each boundary box, enabling a quantitative assessment of the physical presence and completeness of each modelled component in reality.

This method extends beyond mere geometric comparison by incorporating a temporal analysis to identify discrepancies between the actual construction progress and the project schedule as defined by the IFC model. Points within the point cloud that do not correspond to any component in the IFC model are flagged, indicating either elements that are ahead of schedule, behind schedule, or potentially unscheduled additions. Conversely, boundary boxes in the IFC model lacking sufficient point cloud coverage highlight components that are behind schedule or missing from the physical build. This comprehensive analysis allows project managers and stakeholders to assess which components of the construction project visually and quantitatively are aligned with the planned timeline, which are lagging, and which are unexpectedly advanced.

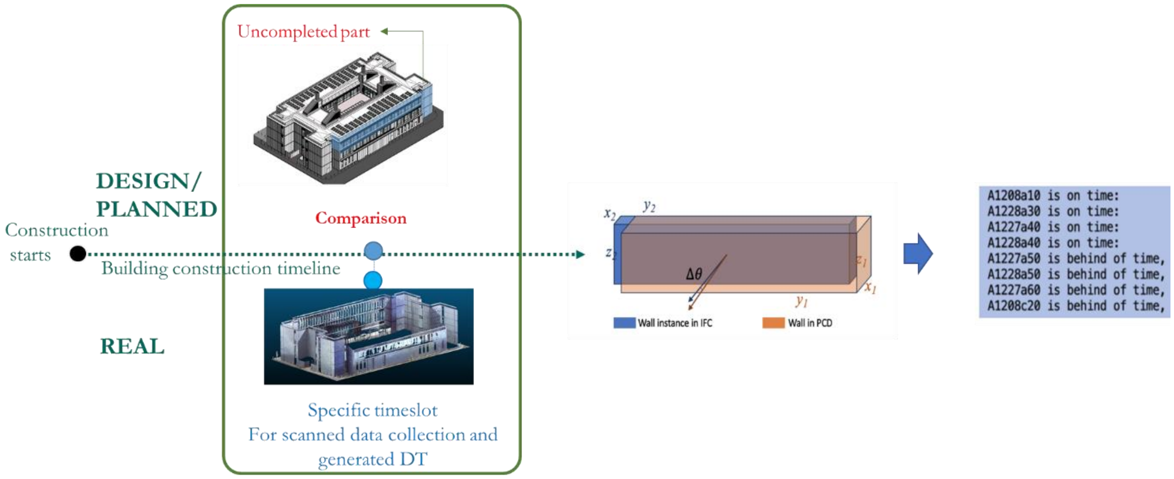


Figure 26. Pipeline of gDT for construction phaseEGNSS data integration

During the scanning process, European Global Navigation Satellite System (EGNSS) data is collected in tandem with the acquisition of image/ LiDAR point clouds through photogrammetry. This simultaneous data collection ensures that each point within the cloud is inherently associated with precise geospatial coordinates, facilitating an immediate and accurate georeferencing of the digital representation. This data is then synchronized with the high-resolution, three-dimensional point cloud data, typically stored in PLY or LAS formats, capturing the physical form of the building with spatial accuracy. The integration process is supported by sophisticated software tools capable of processing and aligning these diverse data types, ensuring that the point cloud is not only geospatially accurate but also ready for the next phase of digital twin construction.

The construction of the digital twin from this enriched point cloud data involves a detailed mapping relationship between the raw point cloud and the final digital twin model, often represented in the Industry Foundation Classes (IFC) format for compatibility with geometric Digital Twin. This mapping process is both complex and technical, requiring advanced algorithms to translate the dense point cloud into a structured digital model that accurately reflects the building's geometry and topology. The EGNSS information, embedded within the point cloud, is seamlessly integrated into the digital twin, providing a geospatially anchored and dimensionally accurate digital representation. This ensures that every component of the digital twin, from structural elements to architectural details, is precisely located in its real-world geographical context. This process will be verified and tested in the further development progress.

3.3.1.5. VR/AR-support DT visualisation

The development of an VR/AR-supported geometric digital twin visualisation platform, leveraging the Unreal Engine, involves a sophisticated technical pipeline designed to render an immersive 3D model of a building, alongside integrated thermal data and EGNSS information. Initially, the process commences with the importation of geometric 3D models into the Unreal Engine, a powerful tool known for its high-fidelity graphics and real-time rendering capabilities. The constructed geometric digital twin model is prepared and optimized for XR environments to ensure seamless performance. Concurrently, thermal data is processed and mapped onto the 3D model.

Furthermore, the integration of EGNSS data into the visualization platform adds a layer of geospatial accuracy and context to the digital twin. This data, indicating the precise location and orientation of the building on the Earth's surface, is crucial for aligning the digital twin within a global context and for supporting simulations that require real-world geographical positioning, such as sunlight analysis or environmental impact studies. The Unreal Engine's robust support for geospatial data ensures that EGNSS coordinates are accurately reflected in the virtual environment, providing users with a true-to-life representation of the building and its surroundings. By combining the detailed geometric model with thermal data visualizations and precise EGNSS information, the platform offers a comprehensive and immersive VR/AR experience.

For the scenario 2 solution in the Pilot Case 1 – MOS, it is designed to show both collected point cloud data and 4D BIM model with the same scene in one interface to further facilitate the visualisation of construction scheduling (see Figure 27).

Sub-interface 1: collected point cloud model

Sub-interface 2: As-designed model or the 4D BIM model with the same view

Figure 27. Design of visualisation platform for construction scenario

3.3.2. Service 2: Digital Twin Enrichment

Service 2 is being rolled out in two of the SE1 cities out of all those that have been targeted by the Digital Twin (SE1) generation.

First, Warsaw (Poland), where the Faculty of Psychology in Warsaw, a recently completed construction, is evaluated. The objective is to evaluate the quality of the envelope to compare it with the initial design estimates. To define the quality of the envelope, thermal bridges, humidity will be detected and, in addition, an analysis of the installation of solar panels on the roof will be carried out.

Secondly, in Piraeus in Greece, this building is an educational school, which was built in 1876 and is being rehabilitated. With the enrichment provided by SE2, the aim is to analyze the envelope to find critical areas and thus be able to intervene in them. These critical areas are thermal bridge detection and classification, dampness, and cracks.

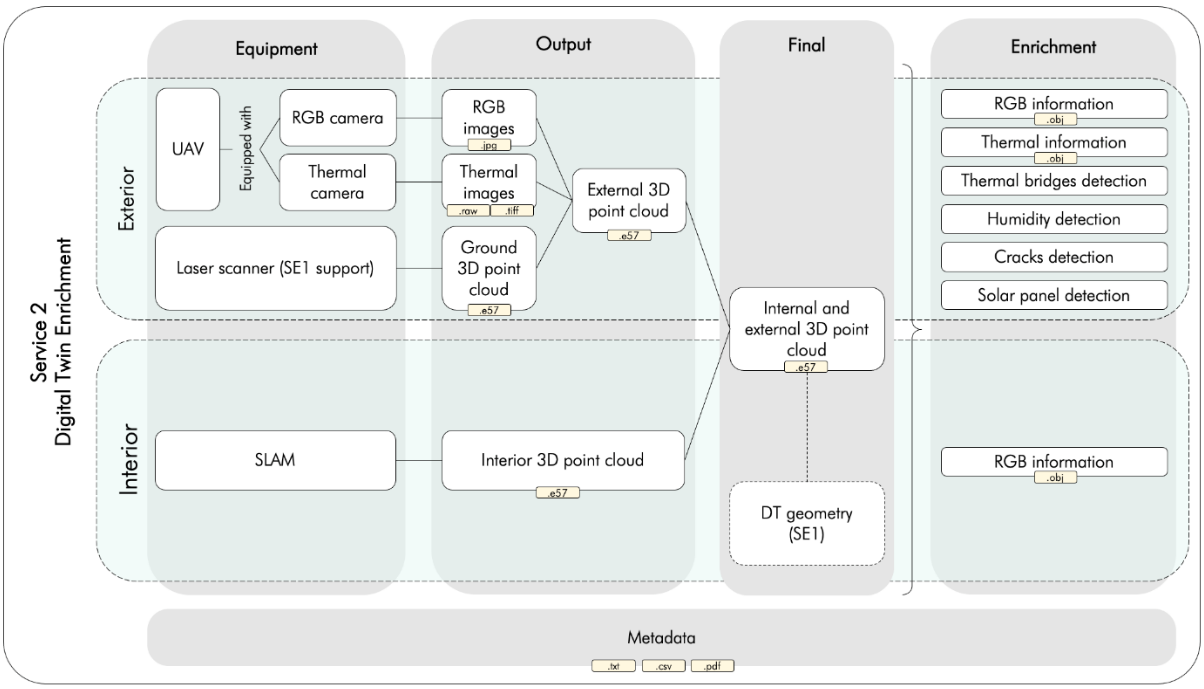


Figure 28. Service 2 Digital Twin Enrichment development

3.3.2.1. Choice of buildings

For the choice of a pilot building to evaluate the service, and in collaboration with the SE1, some necessary requirements were established to reach an optimal result. These requirements can be found in section 9 Annex A: Digital Twin Building Recommendations – Drone Flight.

Mostostal proposed a building that met the necessary characteristics and therefore the decision was quick. On the other hand, in Greece, the choice of building had a longer journey since the first proposal did not meet the necessary characteristics and therefore, it was decided to make a table with the multiple options and the requirements to see which of them fit best (see Figure 29 and Figure 30).

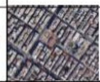
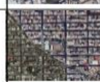
Position	Name	Image		Build-up area	Type of building	Between narrow streets / On main street or wide streets / Nearby park or square	Isolated / in party wall	Number of facades in party walls	Shape	Nº buildings	Levels
1	21st Elementary school			Yes	Educational	Park	Isolated	0	"I"	3	1 2 1
2	14th Gymnasium			Yes	Educational	Main street	Isolated	0	"F"	3	3 3 3
3	2nd primary school			Yes	Educational	Park	In party wall	1	"L"	2	3 3
4	17th Elementary school			Yes	Educational	Narrow streets	Isolated	0	"I"	3	2 3 2
5	9th Elementary			Yes	Educational	Park	Isolated	0	"I"	1	2
6	11th Elementary			Yes	Educational	Narrow streets	Isolated	0	"L"	3	1 2 3
7	Nursing home			Yes	Health	Park	In party wall	2	"H"	2	4 7
8	2nd Night High-School (Skyp)			Yes	Educational	Main street	Isolated	0	"T"	1	3
9	13th High-School			Yes	Educational	Narrow streets	Isolated	0	"L"	3	2 2 2
10	Gymnasium-Kaminia			Yes	Educational	Main street	Isolated	0	"L"	3	2 2 2
11	SEF stadium			No	Stadium	Park	Isolated	0	"O"	1	-

Figure 29. Building selection criteria for Greece (first part)

Curved façade	Narrow spaces (patios)	Large windows	Setback façade	Presence of vegetation	Amount of vegetation	Minimun distance to vegetation (m)	Nº of façades with minimum distance	Presence of cables	Distance to cables (m)	Presence of antennas on roof
No	No	No	No	Yes	Low	3	1	Yes	0	No
No	No	No	Yes (corridor)	Yes	Low	0	2	Yes	2	No
No	No	No	Yes	Yes	Low	0	1	Yes	0	No
No	No	No	No	Yes	Medium	0	1 (large)	Yes	5	No
No	No	No	Yes (windows)	Yes	Medium	0	1 (large)	Yes	0	No
No	No	No	No	Yes	Medium	0	2 (large)	Yes	5	No
No	Yes	No	Yes (corridor and terrace)	Yes	High	0	2	Yes	2	Yes
Yes	No	No	No	Yes	Medium	1	1	Yes	10	No
Yes	No	No	No	Yes	Low	0	1	Yes	3	No
Yes	No	No	No	Yes	Low	0	1	Yes	0	No
Yes	No	Yes	No	No	-	-	-	No	-	No

Figure 30. Building selection criteria for Greece (continuation)

The necessary requirements included the following:

- Building between streets or with a park nearby: this feature does not determine whether the building is suitable or not, but it allows a hypothesis to be generated from the results.
- Number of party wall façades: it was established that the ideal would be buildings with 0 or 1 party-wall facades, 2 façades would be possible and from 3 would no longer be a viable option.
- Shape: Any building with a circular shape would be discarded, the SE1 determined that it would be very complicated to develop a twin with these characteristics.
- Number of buildings or blocks: the surface area to be developed was limited so that the interior scan would not exceed time and budget.
- Levels: buildings with more than 7 levels were discarded.
- Curved façade or large windows: it was not possible for the SE1 to develop the twin of a curved façade, so buildings with these characteristics were discarded.
- Recessed façade: façades without setbacks would be ideal, the drone is not able to obtain data from the parts with setbacks (exterior corridors), so SLAM should be included in areas with these characteristics.

- Presence of vegetation and distance from the façade to the vegetation: buildings with large trees with treetops less than 2 meters would lose much of the information, so buildings with little vegetation near the façades were prioritized.
- Presence of cables: for automated flights, in which a trajectory is established for the drone, and it follows it automatically, cables are elements to be careful with, some are not detectable by drones.
- Presence of antennas or large elements on the roof: the presence of elements means raising the drone and capturing the images at a higher distance, reducing resolution.

3.3.2.2. RGB and Thermal Image Calibration Software

The development of this service level is supported by in-house software designed within the Python framework. Additional processing stages are necessary to achieve optimal results. The following bullet points outline the main contributions of the software to this service level:

- Advanced digital processing for RGB photos: This includes cropping, scaling, colour space conversion, and distortion removal.
- Advanced digital processing for thermal photos: In addition to the aforementioned features, this module incorporates thermal data processing to calibrate image radiometry using specific values of relative humidity, distance, and reflection. Furthermore, it includes algorithms to enhance visual quality, such as edge enhancement, equalization, and normalization.
- Thermal-RGB registration: This module utilizes various algorithms (e.g., RIFT, GLS-MIFT, ASTC) to detect key points in multimodal images, facilitating the establishment of relationships between thermal and RGB images within the dual camera module. Consequently, the software can extract the homography matrix or even the essential/fundamental matrix. The results of this module are illustrated in the following images.

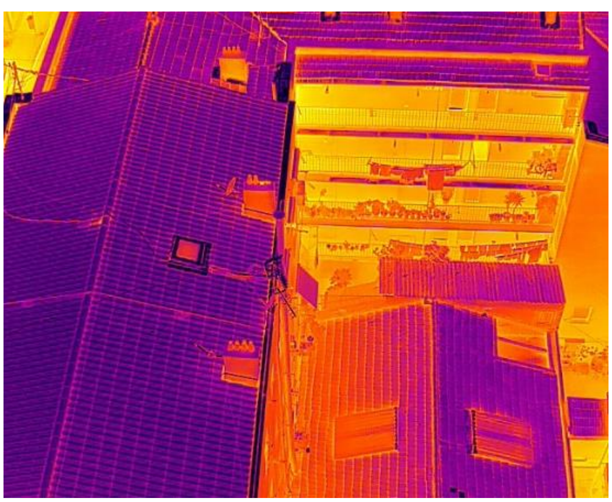


Figure 31. Thermal image

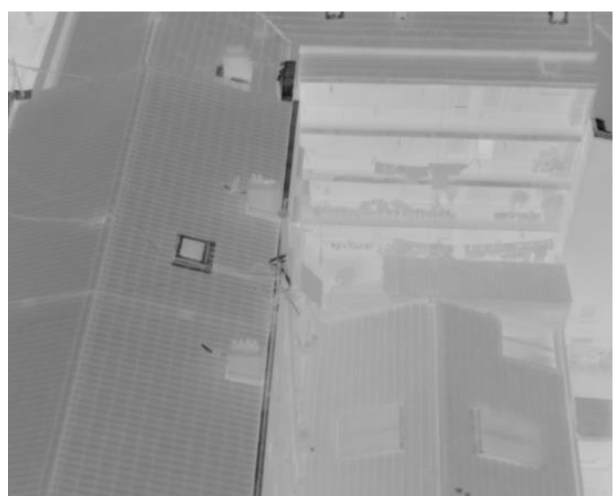


Figure 32. Thermal image (B&W)

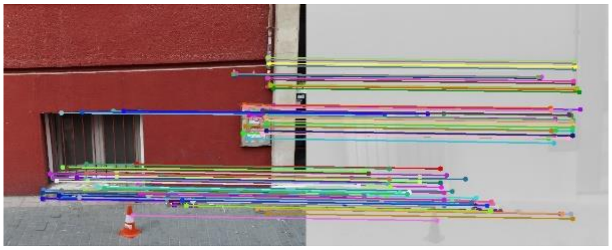


Figure 33. Point matching process

Figure 34. RGB and thermal registration

3.3.2.3. Mesh Processing for Dual Cameras

In this work, we focus on the optimization of drone flights and image processing to obtain point clouds. Nowadays the 3D model is generated by using the Structure from Motion approach, generating one model for the RGB and another model for the thermal information. That implies the processing of two models. To optimize this method, we propose the use of two strategies that allow to process a unique model (RGB) and then project the thermal information. On the one hand we propose the use of a homography transformation (2D transformation). On the other side we propose the stereo calibration that allow to have the relative orientation between RGB and thermal cameras.

In this work, we focus on the optimization of drone flights and image processing to obtain point clouds.

In this project we have drones with dual cameras, they capture infrared and RGB images simultaneously. Both cameras have different positions, parameters, and resolutions, so they must be calibrated simultaneously. Both cameras have different positions, distortion and inner parameters, and resolutions, so they must be calibrated and oriented simultaneously. This is a challenge for the manufacture of the calibration mesh, as it must be observed in both visible and thermal imaging. This mesh will be used to obtain both position and distortion parameters. To this end we have developed a calibration mesh able to deal with this question.

For the manufacture of this mesh, several decisions were made with the recommendation of a company specialized in it.

- Pattern of squares (chess). This makes manual manufacturing easier. It is true that there are other more precise patterns when the mesh is made by non-manual means, but for this situation the most feasible option would be interleaved squares of different colors.
- Black and white colors. This would allow the mesh to be visible in RGB image.
- Difference in materials or paints. To observe both squares with different temperatures in the infrared image it was important that they had different thermal properties, so it was decided to use different materials for each color (black or white) of square.

Test 1

In the first approximation, the following details were decided for the mesh:

Table 5. Characteristics of Mesh 1

	White	Black
Size	2.5 x 2.5 cm	2.5 x 2.5 cm
Material	Insulating Paint	High-E Paint

Figure 35 Mesh manufacturing process

Figure 36 Mesh (option 1)

The hypothesis of the operation of this mesh resided in the difference in emissivity of the paints, one has the function of transmitting heat more easily and the other to avoid the transmission of heat, so the thermal behavior would be different.

After the calibration of the drone, it was observed that the thermal camera had problems detecting the squares, they were practically not visible. This generated two possible causes, the squares were too small to be observed with definition by the thermal camera or that the chosen material was not correct and therefore this difference in surface temperature was not observed.

Figure 37. Drone calibration

Figure 38. Results of the first calibration (RGB and thermal)

The process had not worked as we expected, so it was believed that the most logical thing to do was to test materials prior to the manufacture of a new mesh and measure the different results and parameters with a handheld thermal imaging camera, to assess which was the best option to use in the new mesh that would be manufactured.

Material Testing

The following materials were tested in nine different tests: insulating paint, high-emissivity paint, masking tape, electrical tape, vinyl, faux leather, wadding, thick linen, and satin with sponge.

Of all of them, the homogeneity of the sample was measured in thermal imaging, the average temperature when we provided heat by convection (hair dryer) for 30 seconds and 2 minutes; and the average temperature when we provide heat through radiation (sun) at 2, 5 and 10 minutes of exposure.

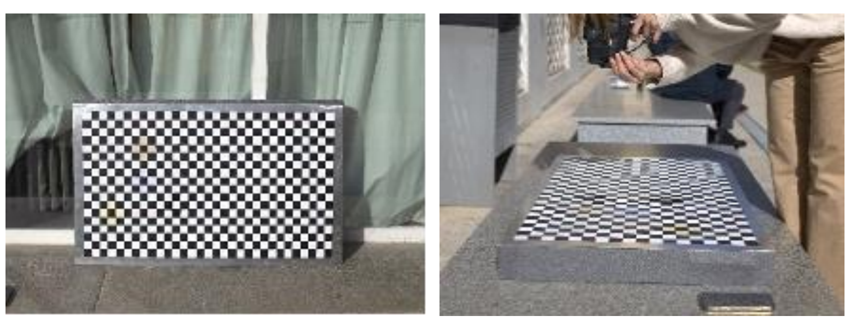


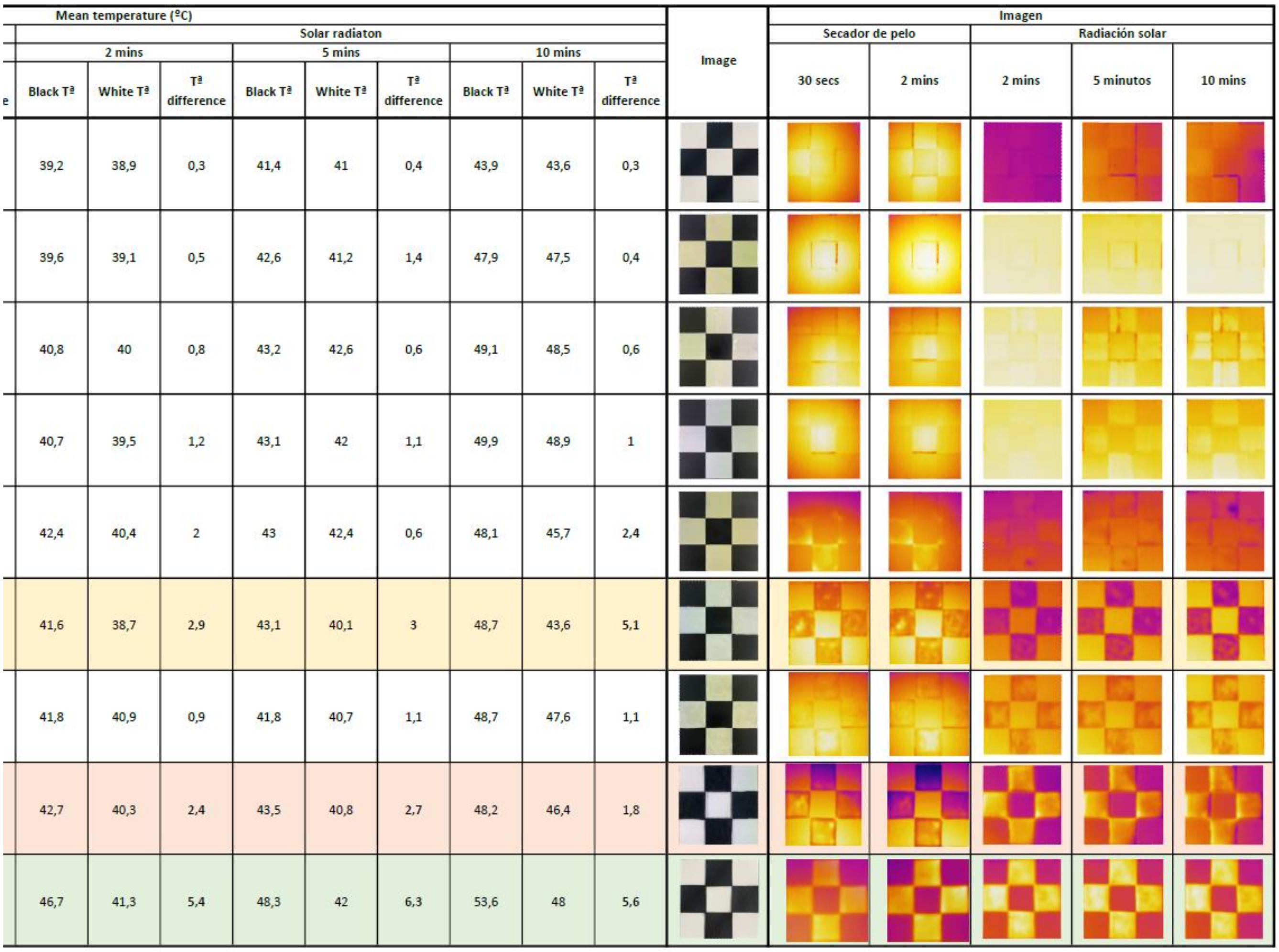
Figure 39. Material Measurement with Handheld Thermal Imaging Camera

From all this, the temperature of the black and white color is obtained, observing the difference in all cases and situations.

This allowed us to choose the best material for the calibration mesh.

	Weather			Material			Distance from surface (m)	Homogeneous (yes/no)	Hairdryer					
									30 secs			2 mins		
	Tª exterior	Humidity	Sky	Base	White	Black			Black Tª	White Tª	Tª difference	Black Tª	White Tª	Tª difference
Material 1	15º	52%	Sunny	Metal plate	Insulating paint	High emisivity paint	0,35	Si	55,6	55,1	0,5	56,2	55,45	0,75
Material 2	15º	52%	Sunny	Metal plate	Masking tape	High emisivity paint	0,35	No	41,6	39,9	1,7	50,4	49,5	0,9
Material 3	15º	52%	Sunny	Metal plate	Insultaing tape	High emisivity paint	0,35	No	52,6	49,7	2,9	60,4	57,5	2,9
Material 4	15º	52%	Sunny	Metal plate	Vynil	High emisivity paint	0,35	No	61,2	60,4	0,8	62,7	61,3	1,4
Material 5	15º	52%	Sunny	Metal plate	Fake leather	High emisivity paint	0,35	Si	55,5	60,7	5,2	63,5	67,5	4
Material 6	15º	52%	Sunny	Metal plate	Wadding	High emisivity paint	0,35	No	41,9	38,4	3,5	64,1	55	9,1
Material 7	15º	52%	Sunny	Metal plate	Thick linen	High emisivity paint	0,35	No	42,9	41,2	1,7	65,4	61,6	3,8
Material 8	15º	52%	Sunny	Metal plate	Insulating paint	Satin with sponge	0,35	No	47,7	56,4	-8,7	44,2	56,9	-12,7
Material 9	15º	52%	Sunny	Metal plate	Insulating paint	Fake leather	0,35	Si	42,6	37,2	5,4	64,8	53,1	11,7

Figure 40. Material measurement results (first part)



Mean temperature (ºC)										Image	Imagen				
	Solar radiaton										Secador de pelo		Radiación solar		
	2 mins			5 mins			10 mins								
e	Black Tª	White Tª	Tª difference	Black Tª	White Tª	Tª difference	Black Tª	White Tª	Tª difference		30 secs	2 mins	2 mins	5 minutos	10 mins
	39,2	38,9	0,3	41,4	41	0,4	43,9	43,6	0,3						
	39,6	39,1	0,5	42,6	41,2	1,4	47,9	47,5	0,4						
	40,8	40	0,8	43,2	42,6	0,6	49,1	48,5	0,6						
	40,7	39,5	1,2	43,1	42	1,1	49,9	48,9	1						
	42,4	40,4	2	43	42,4	0,6	48,1	45,7	2,4						
	41,6	38,7	2,9	43,1	40,1	3	48,7	43,6	5,1						
	41,8	40,9	0,9	41,8	40,7	1,1	48,7	47,6	1,1						
	42,7	40,3	2,4	43,5	40,8	2,7	48,2	46,4	1,8						
	46,7	41,3	5,4	48,3	42	6,3	53,6	48	5,6						

Figure 41. Material measurement results (continuation)

Test 2

After the testing of materials, a clearer conclusion was reached about the materials to be used:

Table 6. Characteristics of Mesh 2

	White	Black
Size	7.5 x 7.5 cm	7.5 x 7.5 cm
Material	Plastic vinyl	Adhesive leatherette

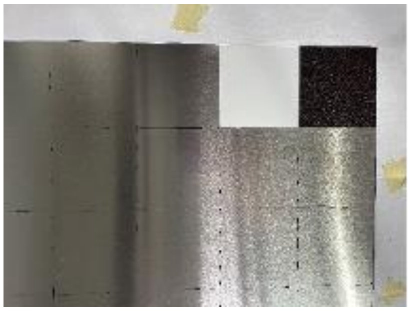


Figure 42. Mesh Manufacturing Process

Figure 43. Mesh (option 2)

The drone was calibrated with the new mesh, obtaining positive results for both RGB and thermal.

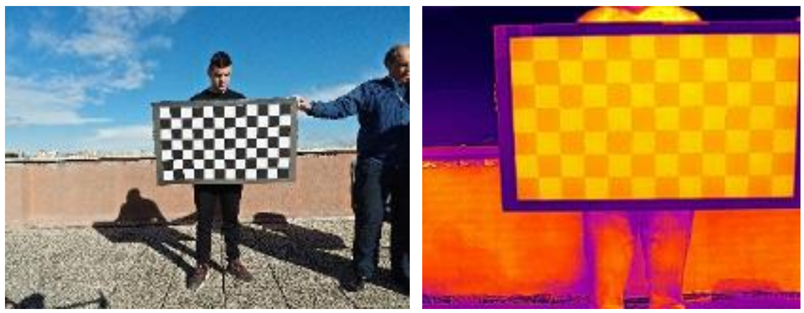


Figure 44. Results of the first calibration (RGB and thermal)

As can be seen in the images, the choice of materials in this second option was more successful. Placing the mesh in the sun for a few minutes acquired different temperatures in each material, so it was easily observable in thermal imaging. This made it possible to obtain the necessary parameters to optimize the next flights to be carried out with this equipment.

Conclusions

The calibration of the camera was necessary for the generation of the 3D model, but the calibration of the camera has also allowed us to reduce flight and image processing times.

The original process consisted of two data processing, one for thermal and one for RGB, but with calibration we managed to reduce it to a single processing with both images. On the other hand, in drone flight, planning should no longer have an overlap of images of the necessary 85%, with the work done, we manage to reduce its overlap. This translates into fewer photographs per flight and reduced drone flight time.

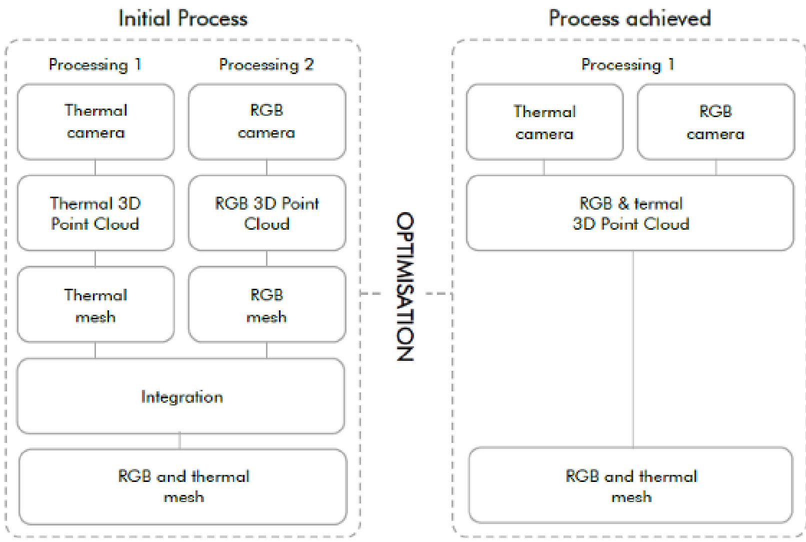


Figure 45. Flight Processing Optimization

3.3.2.4. Flights in Madrid (testing)

With the aim of optimizing flight times and in relation to the previous section, flights are being carried out in Madrid (Spain) within the framework of another project but applying the advances of BUILDSPACE. In this way, we will be able to test the work carried out and ensure the correct operation when flights begin in Greece and Poland.

A total of 4 flights have been carried out, in two different neighborhoods of Madrid. These case studies are larger than those in BUILDSPACE, which creates greater challenges and problems for us now. Of the 4 flights, 2 took place in summer, to observe the quality of the building envelope, in addition, the urban heat island. The other two flights have taken place in winter, to detect thermal bridges.

Each drone flight features vertical, oblique, and horizontal flight. Vertical and oblique flight are used for model and point cloud development; and horizontal flyover, which captures the façade in greater detail, will be used to analyze the facades in greater detail.

Figure 46. Drone Flight Scheduling

Figure 47. dji matrice 300 rtk drone

The drone flown in both case studies is the same one used for mesh calibration.

For the processing of the data, the Structure from Motion approaches has been used, where the images have been processed to obtain the point cloud and the RGB and thermal mesh of the models.

Figure 48. Processing result in Madrid (textured mesh)

3.3.2.5. Critical areas detection (Solar panels)

In the enrichment of the digital twin, not only the RGB and thermal part were found, but critical areas were also detected, and the operation of the photovoltaic panel installations was evaluated.

Comprehensive research on Object Detection algorithms has led us to You Only Look Once (YOLO) algorithm. It applies a single convolutional neural network to the full image, dividing it into regions and predicting bounding boxes and probabilities for each.

Among these, Ultralytics YOLOv8 model represents a state-of-the-art approach in this field. It is known by its versatile framework and computational performance, serving for the different purposes required along this work such as object detection and segmentation tasks.

At this moment, several tests are being conducted with the YOLOv8 model. Ongoing testing is focused on fine-tuning the model and its hyperparameters for an optimal performance of both semantic segmentation by means of a binary mask and object detection on thermal images.

Here are some of the results of the first tests:

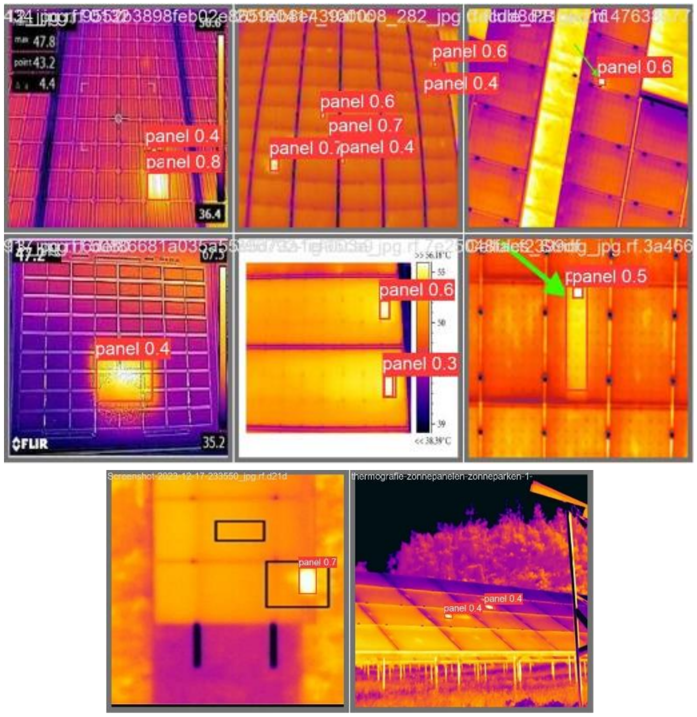


Figure 49. Results obtained for 100 epochs training

3.3.2.6. Replicability

The SE2 can be replicated in all building typologies and cities around the world. There is the future possibility of automating flights, such that flights could be planned to capture buildings or even entire blocks. Subsequently, it would be processed and with the critical area detection software, automatically, humidity, thermal bridges, cracks and malfunctioning solar panels would be detected, in addition, a report of each damage or situation could be downloaded.

This makes it possible to evaluate the situation of each building in cities, generating a platform with 3D meshes or 3D point clouds (RGB and thermal), with temperature and damage information.

4. BUILDSPACE services at city scale: Built Environment Climate Scenarios

The Built Environment Climate Scenarios service (SE3) aims to calculate the current energy demand and consumption of building stocks based on the generation of simplified models. The evolution of such demand and consumption according to different climate change scenarios will also be calculated, according to the standard accepted CMIP6 scenarios (SSPs-RCPs) through the downscaling of climate data and bias-correction with historical data from weather stations. This allows to see the effects of different climate scenarios on the energy performance of building stocks, providing an understanding of how building stock energy demand and consumption will be affected in the future by climate change, which is also key knowledge for urban and energy planners and decision-makers.

The service also includes two more functionalities, one is related to the calculation of relevant KPIs to retrofitting strategy gains, which will be done by defining different retrofitting strategies that can be selected by the user to see the effects of the future climate scenarios on the energy performance of building stock with the application of retrofitting measures, to better analyse the benefits or worthwhile of different interventions.

The second additional functionality is related to the assessment of an area's solar PV potential, as well as on the part of the calculated energy demand that could be covered by PV production (self-consumption). This solar PV potential, together with the energy demand of the building stock, can be assessed both in current and in future scenarios, taking into account the climate change effects. Thus, how climate change affects both the demand of the buildings and the solar potential can be considered in the energy planning.

In deliverable 2.2 "Use cases and design of applications' dashboards" three technical use cases where reported, related to the SE3:

- **UC3.1 – Assessment of energy demand and consumption**: estimation of the energy demand and consumption of the building stock, based on buildings' data (year of construction, geometry, height, use or typology, and other characteristics). It also calculates the energy demand and consumption in the future according to different climate change scenarios (standard accepted CMIP6 scenarios SSPs and RCPs) through the downscaling of climate data and their bias-correction with historical data from weather stations.
- **UC3.2 – Assessment of retrofitting strategies**: calculation of KPIs to retrofitting strategy gains, based on retrofitting measures defined, as well as it's modelling according to climate change scenarios in the future.
- **UC3.3 – Assessment of solar PV potential**: estimation of solar radiation potential, on hourly output, of available rooftop areas and, through a suitability analysis, calculation of the rooftop PV installation potential.

Both UC3.2 and UC3.3 need UC3.1 to be available and executed. There is also some alignment between UC3.2 and UC3.3, as a specific retrofitting strategy or measure will be related to the use of PV self-production (estimated in UC3.3) to cover the heating and cooling demand, consequently reducing the energy consumption of the building.

4.1. Input and Output

The **inputs** needed by the service are the following:

- Basic information to generate the map (**building footprint** of the buildings included in the pilot area):
    - Cadastral data (provided by the pilot)
    - OpenStreetMap maps (https://www.openstreetmap.org/)
- **Buildings' data** needed:
    - Year of construction for all buildings
    - Buildings' geometry (boundary and area, including façade and party walls areas) – obtained from map information in previous bullet point (building footprint
    - Buildings' height
    - Buildings' use and/or typology
    - Building characteristics: thermal characteristics for the envelope, window-to-wall ratio, energy systems (including district heating data), others (e.g. glass reflectivity)
- Digital Surface Model and Digital Terrain Model (**DSM/DTM**) of the pilot area or LiDAR data instead
- High resolution raster images of the pilot area
- **Historical data from weather stations** (at least from 30 years) or historical data in grid format for 30 years
- Data from **PVGIS**: solar radiation and PV production potential according to the PV technology, location, Azimuth and slope (https://re.jrc.ec.europa.eu/pvg_tools/en/)
- Buildings' retrofitting measures information
- Solar data from **GlobalSolarAtlas** (https://globalsolaratlas.info/)
- Future climate data: 3 models and 2 scenarios from 2023 to 2100 (**Copernicus C3S**)

The **outputs** of the service are the **energy demand and primary energy consumption** calculation and visualization in a coloured map of the building stock of the pilot area. Future projections, taking into account three different climate change scenarios, will be also available. Also, as the map is interactive, user will be able to click on each building to see the complete information available for it.

As per the additional service functionalities, service outputs are also related to the KPIs on retrofitting strategy gains (applied to a selected building or group of buildings), to evaluate how the energy demand and consumption change with the application of different retrofitting measures, as well as the same assessment for the future, considering climate change. Last but not least, the output on the solar radiation calculation will be in the form of the estimate value for solar PV potential of different selected buildings.

4.2. Service Workflow

The service aims to mainly support urban stakeholders (urban -and energy- planners, real estate developers, policy makers…) and citizens (homeowners, residents…) in understanding the energy demand and consumption of the building sector in the pilot area, detailing the levels of energy performance at building scale or on aggregated levels (e.g. district level).

The information calculated for this service will be shown in a coloured georeferenced map, complemented by information in figures for more specific data.

In the coloured map, the user can retrieve the desired information at building level or at an aggregation level. The user could browse the maps and click on a building to check more specific information. This information will mainly be the cadastral reference (or building ID), the building area, the average height, the current use, the typology of the building, the year of construction and number of dwellings. It will also contain information on the external façade area (to the different orientations), as well as the party walls area, the roof area, the volume above ground and compacity. Then, information on the estimated values for energy performance (demand, consumption) will be provided. This latter information will be the one that will be used as basis to colour the map, once it is compared with the values of reference for Latvian building energy performance (for buildings label on Energy Performance Certificates or so).

In Figure 50 below, the complete workflow of the service is depicted, with the different functionalities that will be offered to the user.

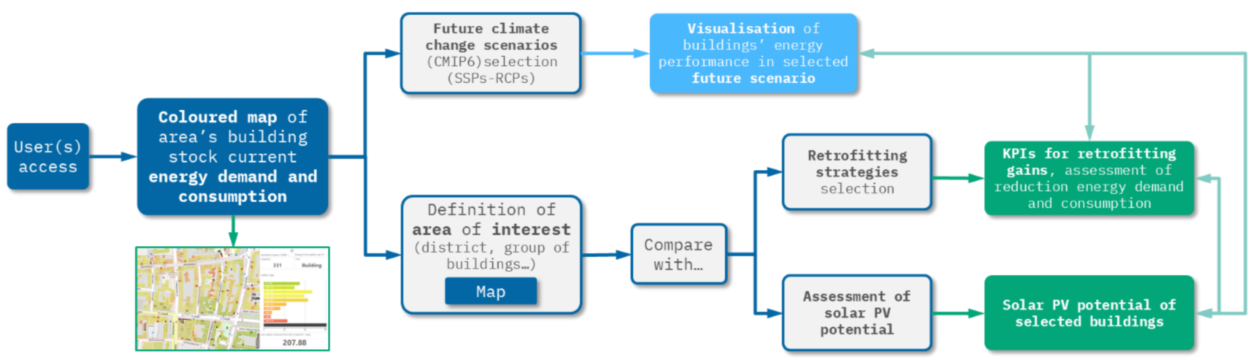


Figure 50. SE3 Built Environment Climate Scenarios workflow

First, the user accesses the service through the BUILDSPACE Core Platform. Then, a map with the Pilot area's building stock will be shown, with coloured information on the buildings' energy performance. Further information of each building can be seen if a user clicks on a building.

Furthermore, a user can select future climate change scenarios from those offered (three options according to CMIP6, as combination of SSPs and RCPs), or the user can define a smaller area of interest (limited to certain number of buildings, due to live calculation time) by drawing the area on the map or by selecting a single building.

For the selected future climate scenarios, the previous values of buildings energy performance in the coloured map will be shown, allowing the comparison between current energy performance and future one. If possible, more comparisons can be done, as for example comparing different future scenarios.

For the option of the defined area of interest, the user can compare the current building energy performance with that that the buildings would have if applying different retrofitting strategies. The user can also obtain the assessment of the solar PV potential on the roofs of the buildings inside the defined area.

Furthermore, for the buildings' energy performance with the application of different retrofitting measures (selected by the user from some pre-defined options), the user can also compare the energy performance of the buildings with the application of such measures in the current year and in the future with a certain climate change scenario. This is very valuable information also for decision-making, both at urban (or energy) planning level, as well as at citizen scale, to really decide on the best retrofitting measure in which to invest, taking into account how the climate will change in the upcoming years. If possible, more comparisons can be done, as for example comparing different retrofitting scenarios.

One of the retrofitting measures that will be offered to the user will be related to the energy systems, in which the heating and cooling of the building could be covered by PV self-production (assessed through the other functionality on roofs' solar PV potential assessment).

Last option that will be given to the user is to view a solar map of the city, with the assessment of the PV potential at building, district or city level. It includes a suitability analysis to exclude any unsuitable areas for potential PV installation, like roofs with northern aspect, high angular slope and underground buildings. This assessment is also performed in the future scenarios, to better know also if the investment is worth related to the production in the upcoming years.

4.3. Application of the service and current progress

The service is being developed for the city of Riga (Latvia), i.e. Pilot 2, in which the service SE3 will provide all information and functionalities at city level.

Data has been collected, with the support of the Riga Pilot leader, RPR. Once the data was collected, an analysis of it has been carried out with the aim to integrate the information coming from the different sources into a single file, specifically a georeferenced file, that is used as the basis for the calculations.

For the first technological release, a neighbourhood of the municipality of Riga was chosen, in agreement within the Riga Pilot, so that it is a representative area of the municipality, including different municipal buildings and private houses and educational buildings.

Cadastral data was analysed and processed, and complemented with OSM data downloaded, to obtain more complete and precise geometries of the building stock (of the selected district in this case). Then, DSM and DTM were integrated and processed to obtain the building heights, and to contrast this data with the cadastral height data. Once the building heights have been corrected through the integration of DSM and DTM outputs, an algorithm to detect adjacent walls was run, to identify the party walls of the buildings and the façade surface for each orientation. Finally, the algorithms developed to estimate the energy demand of the buildings are run. Such algorithms take into account the Heating and Cooling Degree Hours (HDH and CDH), the building area, the transmittance (U) values (defined according to the year of construction of the building, as well as its typology), the gains are subtracted (solar gains, estimated taking into account the wall orientation and the solar radiation in each orientation; as well as gains by the occupancy and other uses, as lighting), and finally, a heating (and cooling) schedule is added.

Then, the energy label values and colour scale to the energy demand obtained are applied, aligned with the Latvian EPC (Energy Performance Certificate) regulation and labelling scale. As the scale for the Latvian EPCs is continued, it has been converted to a scale with steps, in order to leave the following colours fixed according to the values of the energy performance, in kWh/m^2·year (Figure 51).

Figure 51. Above, the colour scale used for the Energy Performance Certificates in Latvia. Below, the scale of colours rectified to be used to colour the map of SE3. Both are in kWh/ m2·year

This first release of the SE3 can be accessed through this link, where both the geojson and the QGZ file (this latter for visualisation, to be opened with QGIS) are uploaded. In the Figure 52, the heating demand map for the first release developed for the Riga district selected as pilot can be seen.

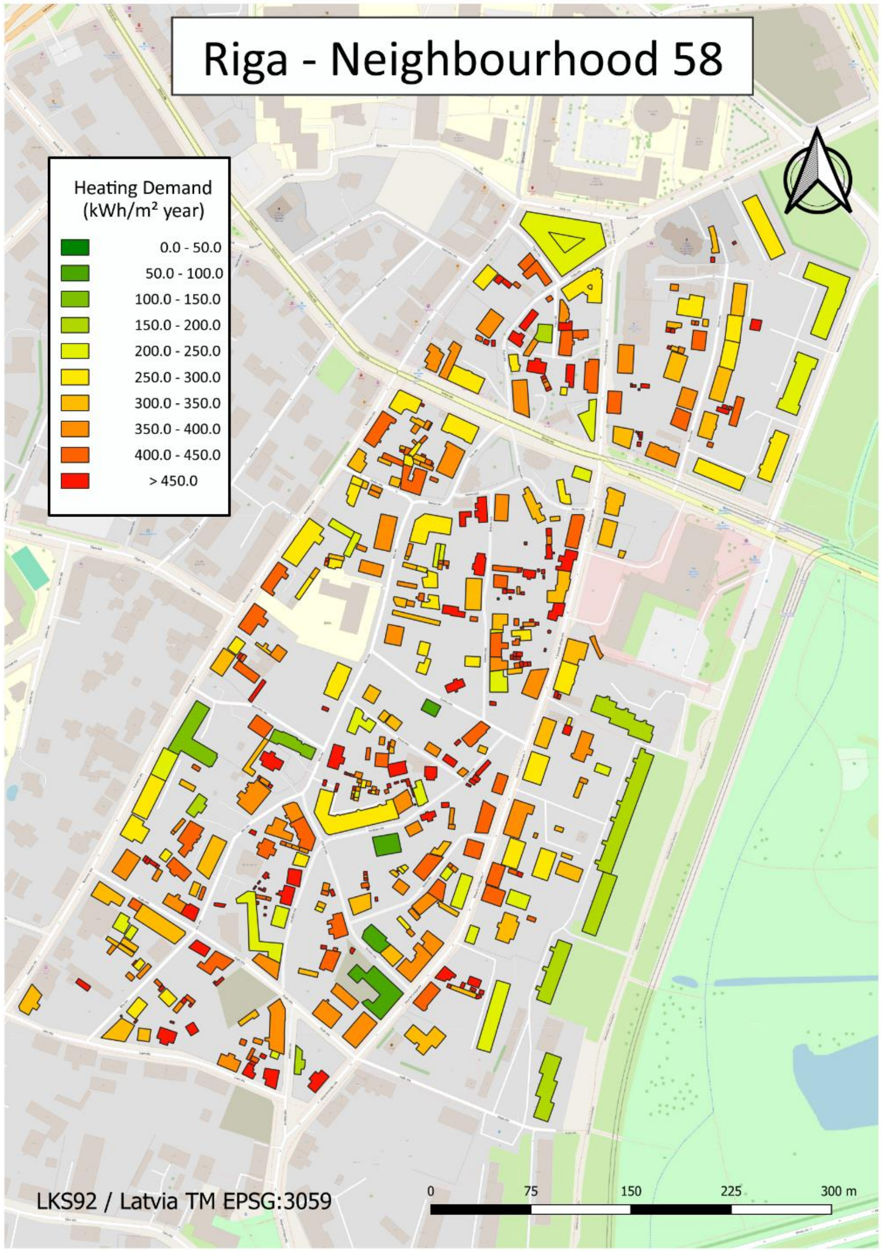


Figure 52. Map of the heating demand for the Pilot neighbourhood of the first release in Riga, Latvia

With respect to the PV potential functionality of the service, a GIS tool and geo-referenced cadastral information is implemented. In this case, the capabilities of ArcGIS Pro were implemented to create a suitable Geo-database and base-map. Once the implementation of the suitability analysis for the available rooftops took place, solar radiation, irradiation, transmittivity and diffusion of the area were considered, to estimate the potential usable solar radiation of every suitable rooftop. For the first technological release, the output of the solar map is calculated in MWh/year of usable solar radiation for every rooftop. Additionally, through the Global Solar Atlas database, the specific photovoltaic power output was taken into account, to transform the usable solar radiation in potential max PV output in MWh/year for every rooftop.

In Figure 53, the rooftops are highlighted with different colour patterns according to the PV electricity production estimation in MWh/year. Darker colours showcasing a low PV output, while brighter colours represent a larger PV output (Figure 54).

Figure 53. Solar map of the Pilot neighbourhood, Riga, Latvia

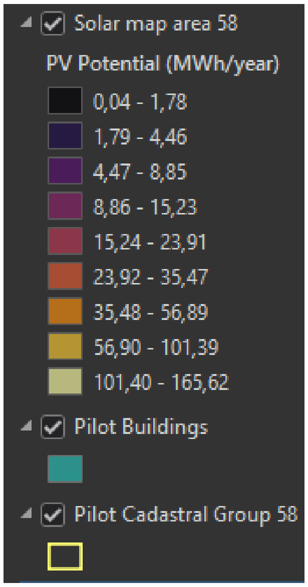


Figure 54. Colour reference of yearly PV output in MWh

Other estimated values included in the attribute table, such as available roof area and initial installation cost, will offer an important insight to both policy makers and citizens.

This first release of the PV potential functionality can be accessed through this link. This functionality will be integrated into the main service for the next release.

This whole process that has been done for a Riga district, can be replicated for the whole city. It is important also to highlight that the workflow, both for the service use and for its technical development, has previously been stablished and it will be followed in the next steps.

With this information, the functionalities indicated in the testbed scenario that is being provided in this first release are covered.

The selection of the city of Riga to develop this service ensures the replicability and upscaling of the service across Europe and beyond. Riga covers different typologies of (residential) buildings that are example of European typologies. The approach used is based on OpenStreetMap data merged with relevant data from Cadastre, to obtain a better dataset. Although both data should be analysed in each particular pilot to see the level of detail of each and the usefulness of the data needed to build the service functionalities. The approach used for the different functionalities is, after the abovementioned data needed, not limited to the choice of geographical regions, locations and typical residential building typologies. It is designed as an user-friendly (with a focus also on citizens and building/dwelling owners as users) and universal service, if there are adequate and sufficient data for the generation of the base map.

5. BUILDSPACE services at city scale: Urban Heat Analysis and Resilience

This service will analyse urban heat at high resolution and will combine demographic data to calculate the so-called urban heat risk and assess social vulnerability to heat. The service will combine the high-resolution urban heat analysis with socio-economic and demography data to evaluate the impact of Urban Heat Islands (UHI) and other microclimatic phenomena on the energy performance of buildings. The service will incorporate a decision support tool that will guide urban stakeholder's adaptation and mitigation strategies to climate change at building-neighbourhood scales.

This service also includes the creation of long temporal series of temperature and relative humidity for different Urban Climate Zones within the city to improve the urban assessment for present and future climate scenarios (e.g. weather files for the energy performance of buildings). UCZ are the result of sub-municipal climate zoning based on climate severity. Also, the service will be designed in such a way as to facilitate its replicability on a European scale.

In deliverable 2.2 "Use cases and design of applications' dashboards" three technical use cases were reported related to SE4:

- **UC4.1 – Urban Heat Risk analysis:** This use case corresponds to the calculation of the Urban Heat Risk (UHR) which is estimated by overlaying information on heat exposure and vulnerability. This will be calculated for the present and future climate scenarios from the IPCC report (SSPs-RCPs). The following information will be the output of the use case: A georeferenced map with the UHR calculated for the selected area and identification of Urban Heat hotspots. A tool will be available to make a comparison between different climate scenarios (present and future).
- **UC4.2 – Urban Heat Exposure:** Calculation of the Urban Heat Exposure (UHE) based on the present and future climate scenarios and most importantly, considering the effect of urban heat. Building characteristics are also considered, such as year of construction, energy performance, etc. The information is displayed in a map with a colour palette. The following information will be the output of the use case: A georeferenced map according to the selection of the user (e.g. present/future climate scenarios), this will also update the UHR map; layer with building stock information; hotspots with the most exposed areas to urban heat; baseline indicator for building's energy performance that can be compared with another layer with the same information but considering the impact of urban heat.
- **UC4.3 – Urban Heat Vulnerability:** This use case is the calculation of the Urban Heat Vulnerability (UHV), based on demographic and socio-economic indicators. Also, it calculates the capacity to adapt depending on the possibilities for intervention in the city. The following information will be the output of the use case: a georeferenced map with the UHV and hotspots identifying the most vulnerable areas within the city, information obtained from the indicators used and comparison results, recommendations for adaptation and mitigation solutions that can be implemented in the hotspots.

5.1. Input and Output

The first output of the service is the Urban Heat Risk, which will be visualised in a coloured map. This risk map builds on three other maps: Urban Heat Vulnerability, Urban Heat Exposure and Urban Heat Hazard. For each of these maps, hotspots will be delimited to identify priority areas for intervention.

In addition to the service, Urban Climate Zones (UCZ) will be determined for which weather files will be generated, both for the representation of current and future climate. These weather files will be available for download, allowing their use in the energy assessment of the building stock and comparison of the urban heat impact on the energy profile of buildings.

The map can be used interactively to identify possible urban heat adaptation and mitigation solutions that respond to site-specific characteristics. The maps with their values, the information on the energy profile of the buildings and the proposed solutions can be incorporated into a summary report. The results will also be available to download (e.g. GIS data).

The inputs needed by the service are the following:

- Open source and standardised meteorological data (minimum 1 year)
- Statistical georeferenced socio-economic and demographic data
- Building stock information: year of construction, typology, energy certificate
- Satellite-derived data such as geospatial land use information, thermal bands, infra-red bands, NDVI, true colour data, high resolution RGB band.

The outputs of the service will be the urban heat risk map displayed through an interactive high-resolution cartographic representation. Information contained will incorporate suitable adaptation and mitigation strategies to climate change at building and neighbourhood scales. It will allow the user to identify, through urban heat and socioeconomic indicators, the social vulnerability to heat.

Additionally, the Urban Climate Zones map will be available which will include the option to download long temporal series of temperature and relative humidity, and weather files for the current and future climate scenarios according to the last IPCC report.

5.2. Service Workflow

This service is intended to serve as a decision support tool for policy makers, but also, to serve as a tool for the scientific community and urban stakeholders, and to provide information to the citizens regarding the urban heat risk in the pilot area.

First, the user opens the service application and selects the city they want to explore. Then, an Urban Heat Risk map is displayed and the option to switch to other climate scenarios (according to the latest IPCC Report, AR6) appears in a window. By selecting another climate scenario, the Urban Heat Risk map is automatically updated and at this point a basic report can be generated.

If the user profile needs more detailed information, they can log in to the application where the comparison tool of different variables such as urban heat hazard, urban heat vulnerability and future climate scenarios will be enabled. If both the hazard and the vulnerability maps are modified, the risk map is automatically updated. On top of this, a layer can be added identifying Urban Heat Risk hotspots for which a range of adaptation and mitigation solutions will be available.

Additionally, the Urban Climate Zones can be visualised and the weather files associated with each of them can be downloaded. It will also be possible to compare the energy demand of the building stock taking into consideration the impact of urban heat on the energy performance. Finally, it will be possible to generate both a general report and download the results data (e.g. GIS data).

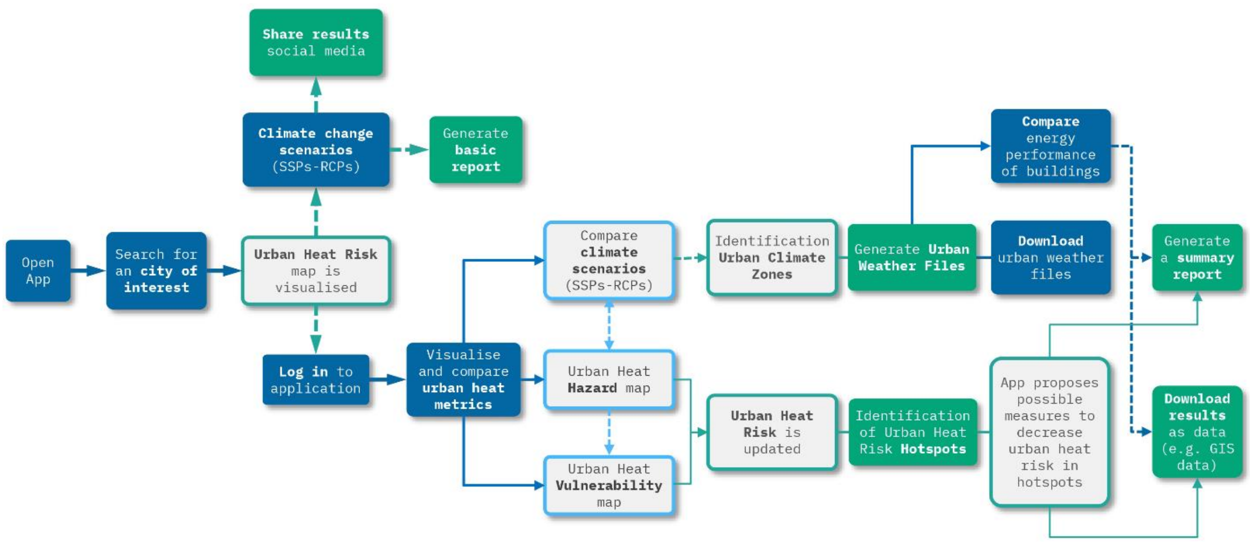


Figure 55. SE4 Urban Heat Analysis and Resilience workflow

5.3. Application of the service and current progress

The service is being developed for Piraeus city, Pilot 3, which is one of the largest Greek urban centres and most important European ports.

The work carried out so far has consisted of the following tasks:

1. Search for sources of non-conventional climate data to be used in the urban heat hazard analysis. To this end, an exploration of two Citizens Weather Stations' databases was carried out: Netatmo and Weather Underground. This included accessing the online sensor's location, integrating them in an offline GIS, and developing analyses of data availability and spatial representativity.
2. Exploration of ERA5-Land Reanalysis to be used as regional climatic reference for the Urban Heat Hazard analysis. A script was created to access hourly weather data through Copernicus' Climate Change Service API. Another script was needed to extract from the NetCDF dataset the needed inputs for the urban heat data morphing.

3. For the vulnerability assessment, a review of the scientific literature has been carried out to identify the indicators that will be used to perform the analysis. On the other hand, some socio-economic and demographic databases were identified to ensure that they are open and standardised. Efforts are currently focused on improving the spatial resolution of these data, which is foreseen for the second technology release. MoP has also provided information on the data they have available that can be of use to the service.
4. Recently, the Cadastre has set up a web page from which data can be requested. Although MoP has direct access to the data to be used in the service, procedures and deadlines for data requests will be explored with the aim of standardisation and replicability of the service. The same will be done for the 2021 Census data collection.
5. Meetings were held with CARTIF to explore how the energy profile of buildings can be integrated according to the description of T3.4 in the GA. In this respect, the feasibility of this service functionality will be supported by the integration of the energy profile of the building stock from the demand side perspective. This also makes sense from the perspective of vulnerable households, who tend to be more restrictive in the use of air-conditioning equipment or even have no air-conditioning equipment at all, thus depending on the passive behaviour of the building.

The first release of the SE4 can be accessed through this link, which contains the compilation of the vulnerability indicators; ERA5 DATA downloaded and a Geodatabase with relevant layers used in GIS (Netatmo and Wunderground points; Athens Local Climate Zones and districts). By the end of the pre-pilot phase (M16) the service will output a preliminary version to the Urban Heat Hazard map based on the CWS and ERA5 data, as well as preliminary Urban Heat Vulnerability and Urban Heat Exposure map.

src\data\make_dataset_01_download_era5_data.py

```python
"""Script for downloading ERA5 data using the CDS API"""

# Modules to be imported
import os
import ast
import cdsapi
import pandas as pd

### FUNCTIONS NEEDED TO DOWNLOAD ERA5 DATA
def load_request_file():
    ''' Function to load the .csv file with the API request(s)'''
    # Define path to .csv file contaning the API requests.
    parent_directory = os.path.dirname(os.path.abspath('__file__'))
    directory_name = os.path.join(parent_directory, 'Requests_ERA5.csv')
    # Import .csv file with requests
    era5_requests = pd.read_csv(directory_name)
    return parent_directory, era5_requests

def identify_request_source(single_request):
    '''Function to identify the data source in the API request .csv file'''
    request_source = ast.literal_eval(single_request.split("retrieve(")[1].split(',')[0].strip())
    return request_source

def identify_body_request(single_request):
    '''Function to identify the body of the API request and create a dictionary'''
    request_body = single_request.split('{', 1)[1].split('\'format')[0].strip()[:-1]
    request_body = ast.literal_eval('{' + request_body + ',\'format\': \'netcdf\',}')
    return request_body

def define_file_name(request_body):
    '''Function to define the saving name of the downloaded file'''
    file_name = request_body['product_type'] + '_' + request_body['variable'] + '_' + \
        request_body['year'][0][-2:] + '-' + request_body['year'][-1][-2:] + '_' + \
        request_body['month'][0] +'-' + request_body['month'][-1] + '_' + \
        request_body['day'][0] + '-' +  request_body['day'][-1] + '_' + \
        request_body['time'][0][:2] + '-' + request_body['time'][-1][:2] + '.nc'
    return file_name
```

Figure 56. Example of ERA5 data download request

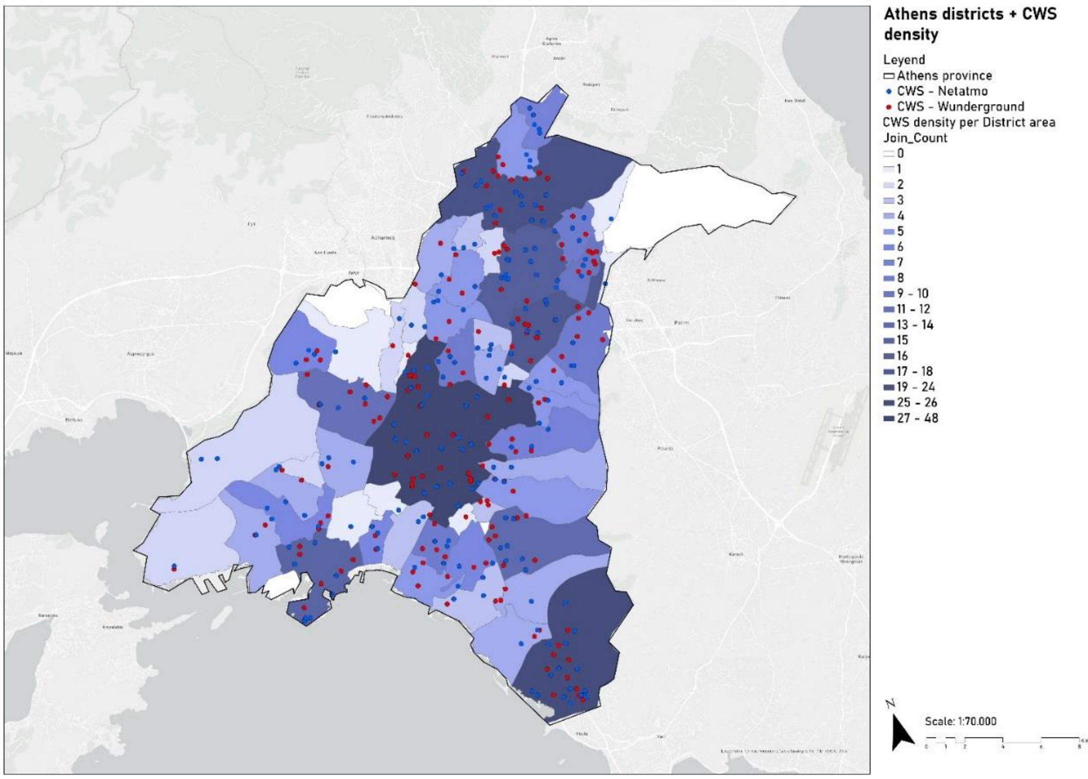


Figure 57. Distribution of the Citizen Weather Stations (Netatmo and Wunderground) in Athens districts

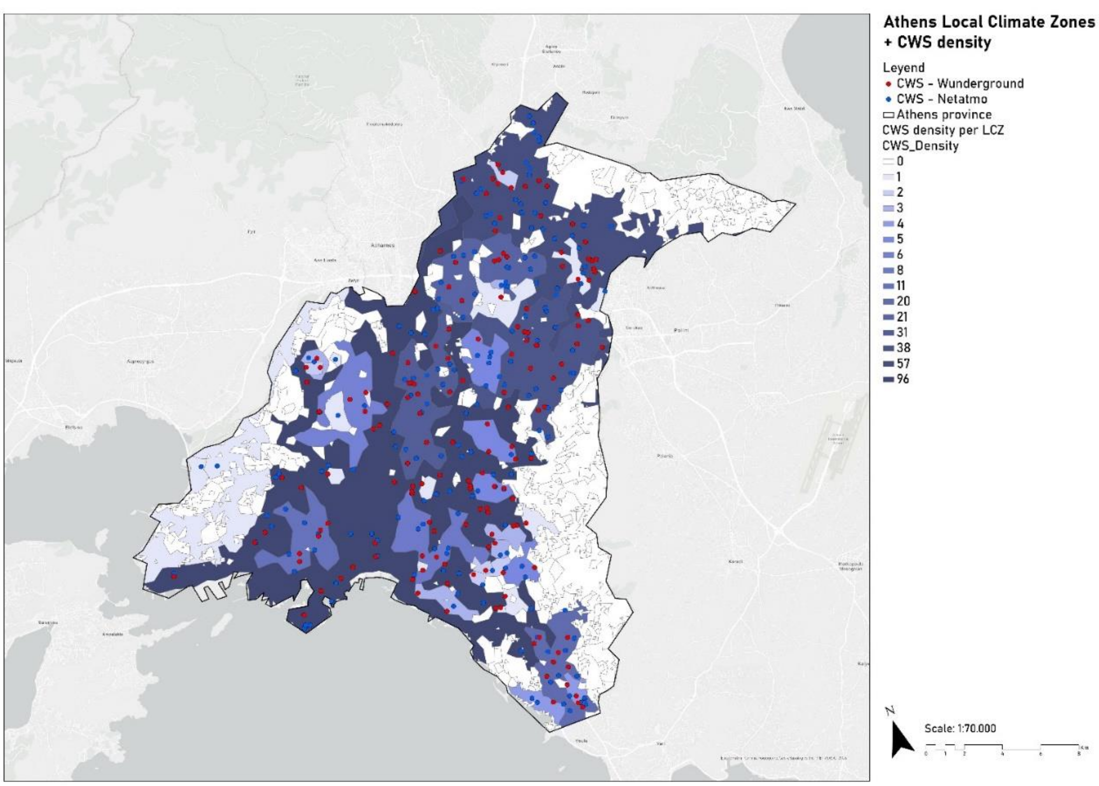


Figure 58. Distribution of the Citizen Weather Stations (Netatmo and Wunderground) in Athens Local Climate Zones

6. BUILDSPACE services at city scale: Urban Flood Analysis and Resilience

The Urban Flood Analysis and Resilience service (SE5) aims to calculate and visualise the expected flood damage to the building stock and flood vulnerability hotspots with the impact of different structural blue-green infrastructure (BGI) and non-structural measures. It provides calculations and visualisations for the future according to different climate-driven scenarios in line with the standard accepted RCPs. The service also provides relevant condition guidance for the design and implementation of building retrofits and BGI measures through a decision support tool.

In this way, SE5 will provide a decision support service to assist urban stakeholders in planning for the maintenance and retrofitting of the building stock against climate change risk, using simplified models for short- to long-term predictions, and to promote the implementation of BGI measures at building and neighbourhood level.

In deliverable 2.2 “Use cases and design of applications’ dashboards” two technical use cases were reported related to the SE5:

- **UC5.1 – Flood Damage Hotspots:** This use case is the calculation of expected flood damage to buildings due to fluvial flooding using online application-based visualisations. Damage per building is assessed using the FDAM methodology by overlaying flood extent map, flood depth, building and public infrastructure data. The evolution of flood damage according to different climate-induced flood change scenarios will be also calculated and visualised, according to the standard accepted scenarios RCPs.
- **UC5.2 – Blue-green Infrastructure Impact:** This use case corresponds to the assessment of the potential of BGI to influence flood vulnerability and resilience by calculating the blue-green factor to land use area using administrative, Copernicus satellite and field data. The hydrological impact of different BGI measures will be calculated based on retrofitting measures defined, as well as it's modelling according to climate-induced change scenarios to urban hydrology in the future.

6.1. Input and Output

The inputs of the service are administrative data (buildings and consolidated cadastre of public infrastructure, current and planned land use, registry of spatial units, registry of assets, water cadastre, floods extend map, protection regimes of cultural heritage), Copernicus satellite data (CLMS data from The High-Resolution Layers Service, Land Use data), flood damage values as model data, and sensors data (temperature, humidity, and precipitation).

The output of the service is the Flood Damage Hotspots in the first use case, visualising Expected flood damage to buildings for a selected area, and in the second use case Runoff volumes hotspots and Blue-green factor per land use unit, both with the application of some BGI measures. The service provides visualisations in a coloured georeferenced map, tables and graphs, and offers visualisations for the present and different climate (precipitation) change scenarios. In the scope of the service, a catalogue of different BGI measures with condition instructions for building renovations will be created.

6.2. Service Workflow

In Figure 59 below, the complete workflow of the service is depicted, with the different functionalities that will be offered to the user.

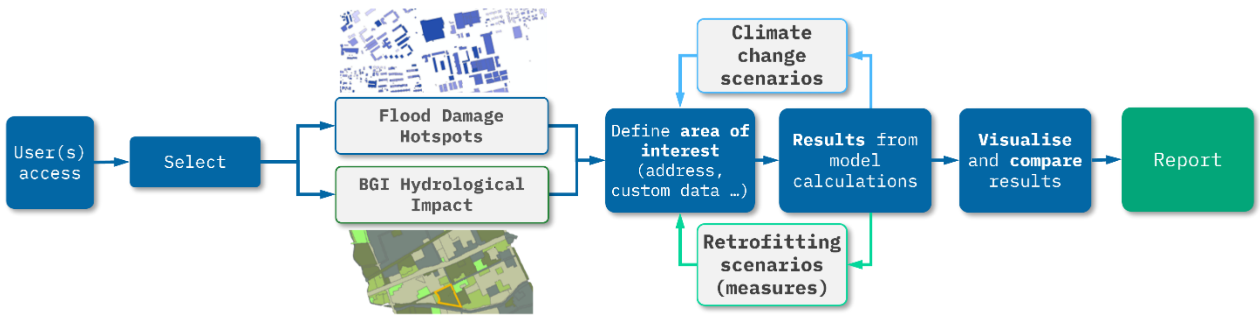


Figure 59. SE5 Urban Flood Analysis and Resilience workflow

When the user opens the service application, a standard map appears in the web platform, showing the pilot area (Ljubljana metropolitan area) and the user can select from two topic modules “Flood Damage Hotspots” or “BGI Hydrological Impact”.

When the user selects the "Flood Damage Hotspots" module, the map of flood extend from current model scenario of all pilot areas is displayed. The user can select the area of interest either by uploading their own data (e.g. shapefile or geojson) or by drawing it directly in the application using a drawing tool. The building stock is then displayed with the data result of model calculations with attributes for the selected buildings, and the expected annual flood damage hotspots are visualised in a red colour scale according to the value of the flood damage. The scenario menu to switch to other climate and retrofit scenarios appears in the window. The user can select and compare different current flood scenarios, flood scenarios due to climate change and adaptation scenarios due to non-structural measures. Finally, a generic report can be generated with information and comparisons of expected flood damage.

When the user selects the "BGI Hydrological Impact" module, the map of green areas is displayed. The user selects the area of interest (either typing, zooming, by uploading own data, e.g., shapefile or geojson, drawing it directly in the application by a drawing tool). Then, on the map appears the building stock with data result from model calculations with runoff volumes hotspots in blue colour scale according to the value of runoff volumes, and visualised in a green colour scale according to the value of Blue-green factor. The scenario menu to switch to other climate and retrofit scenarios appears in the window. There are three options for this: 1) Comparing the statistics with another area. For this, the process from identifying an area of interest until receiving extra info about the area will need to be done again. 2) Selecting different measures: A list of possible BGI measures will be offered. A user can select a measure. If a measure has been selected, the model needs to be ran again to calculate the new results. 3) Selecting different climate scenarios. Same as option 2, but with different climate scenarios. Also, for this option, the model will need to run again.

Additionally, if the user clicks on one building or area, there is shown a value of Blue-green factor and runoff visualisation diagrams (a runoff volume, precipitation high, runoff hydrogram).

If the user needs more detailed information, they can log in to the application where a shapefile available for downloading as well as a detailed expected analysis report in PDF and table or graph can be generated.

6.3. Application of the service and current progress

The service is being developed for the Ljubljana Urban Region, i.e. Pilot 4, the central and most important urban area in Slovenia. The service will provide all information and functionalities at the city level.

Administrative data has been collected for the whole pilot area and integrated into some created GIS georeferenced files, which are used as a basis for calculations. In the pre-pilot phase, we worked on the use case Flood Damage Hotspots and explored the functionality of SE5 through defined inputs, actions and expected outcomes. The flood damage hotspot map of the pilot area was created by visualising flood damage hotspots on a red colour scale according to the value of flood damage. For now, only buildings are considered, but this will be expanded to include other land uses later. Three different pre-calculated flood extends, three different climate change scenarios and three different retrofitting scenarios as anti-flood measures were used. To test the visualisation options, the calculations were done in advance and not directly by the application.

In the following figures (Figure 60, Figure 61 and Figure 62), some screenshots of the drawing application with limited features that have been made so far are shown.

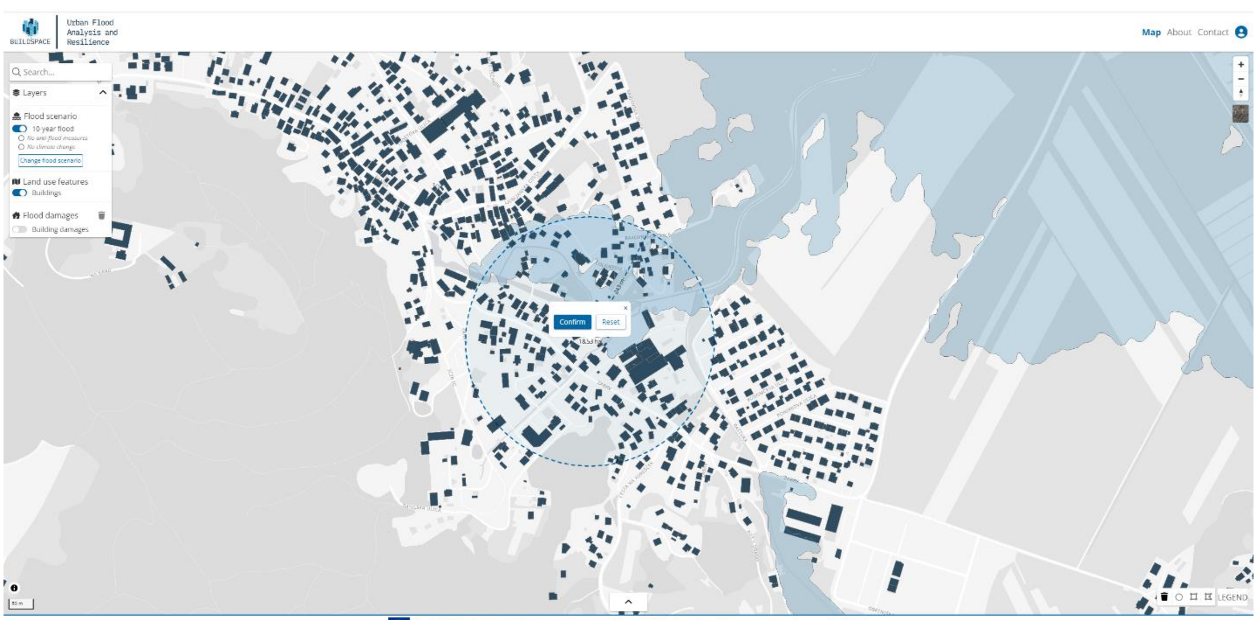


Figure 60. Screenshot 1. The user can select the area of interest by it directly in the application using a drawing tool

Figure 61. Screenshot 2. After confirming the selected area, the building stock is displayed with the data result of model calculations with attributes for the selected buildings, and the expected annual flood damage hotspots are visualised in a red colour scale according to the value of the flood damage

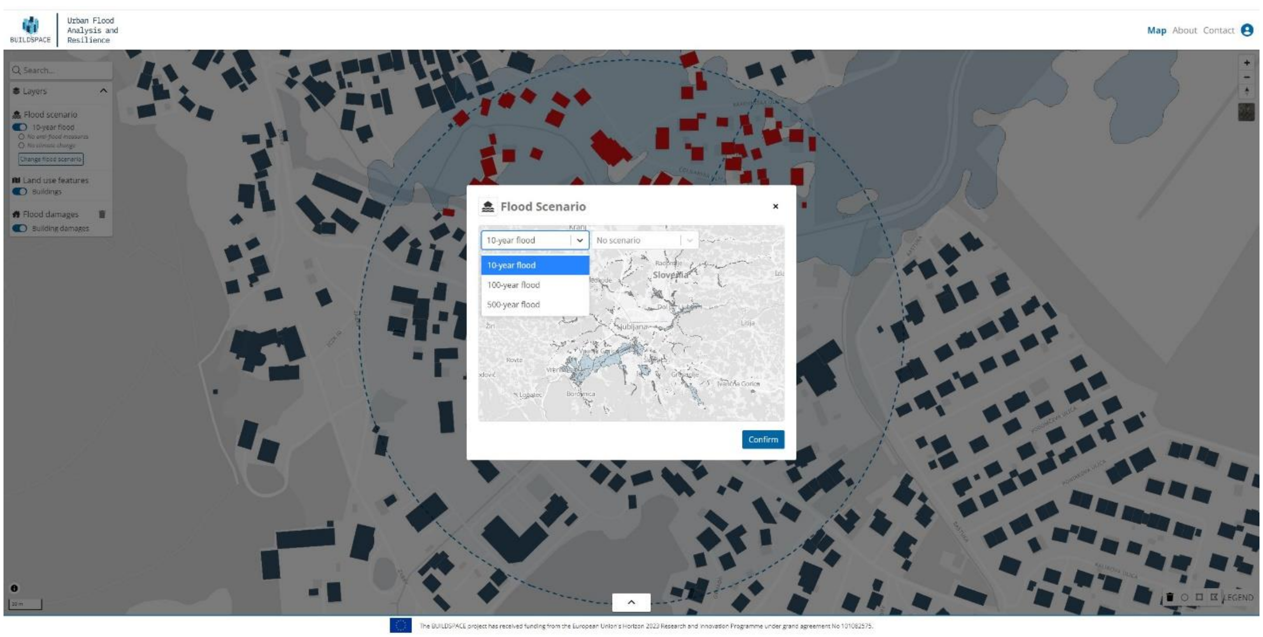


Figure 62. Screenshot 3. Then, by scenario menu it can be switched to other flood extand and corresponding climate and retrofit scenarios

In this first pre-pilot version, a simple application with limited features was built. The application can be accessed via this link: **https://buildspace.nazkamapps.com/** (temporary credentials: username: buildspace@nazka.be, password: Tester2024!). The application in its current state gives a user the possibility to visualise the three pre-calculated floods with statistical return periods of 10, 100 or 500 years. The user can choose to modify the floods by including climate change (expanding the flood) or anti-flood measures (decreasing the flood). When a user has selected the desired simulated flood, he can draw an area of interest by using the drawing functionality. The application will then calculate the flood damages for all buildings that are flooded in the area of interest, based on the surface area of the buildings. The results are shown visually on the map as well as by graphs and tables in the bottom panel.

The choice of the Ljubljana Urban Region as a pilot area enables the replication and scaling up of SE5 results across Europe and beyond. This rather large pilot area covers all typical types of existing buildings in residential and non-residential areas. The approach used, the FDAM methodology and the blue-green factor, is also not limited in the choice of geographical regions, locations and typical building types. It is designed as a universal service – but the appropriate data need to be provided. As alternative data, Copernicus services data will be used and tested in the Full Pilot Operation and Large Scale Operation phases.

In addition, to assess the impact of blue-green infrastructure implementation on land use areas, a review of the scientific literature was carried out to identify the satellite data that we could use.

7. Conclusions

BUILDSPACE **WP3 "BUILDSPACE location-based and remote sensing applications development"** main objective is to coordinate and carry out the specific activities to ensure the development, deployment and validation of the BUILDSPACE platform and services.

The project will create an interoperable platform that offers added value services at building and at city scale. **Services at building scale** enable the **Digital Twin (DT) generation** of buildings (**SE1**) and its **semantic enrichment** (**SE2**) with thermography data collected by drones to support building construction as well as building renovation and monitoring. **Services at city scale** rely on a mix of Copernicus and IoT data to infer visualisations related to **energy demand** (**SE3**), **urban heat** (**SE4**) and **urban flood** (**SE5**) analysis and assessment at urban scales, facilitating decision making for increased resilience of the building stock.

The present document D3.1 "BUILDSPACE core platform and services" is the **first iteration of the BUILDSPACE core platform and services**, where the **first technology release** is presented. As such, it presents the Core Platform and each of the services and outlines their current development status.

The second iteration, which corresponds to the second technology release of the project, will be delivered in October 2024 (M21) through the D3.2 "BUILDSPACE core platform and services (interim)". This is a major milestone of the project, and the Core Platform and each service has already planned that delivery as can be seen in Table 1, in section 1.2. To get there, the next steps of the services are to meet with their related pilots in order to present the first release and obtain feedback and comments, as well as to prepare the mock-ups of each, that will be delivered in May 2024 in D2.3 "BUILDSPACE specifications and architecture", as part of Task 2.4 "Co-design innovative user-friendly environments". Then, each developer will continue working on the technological development and deployment of the services and core platform to finally achieve the functionalities and deliveries set for the second release.

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9. Annex A: Digital Twin Building Recommendations – Drone Flight

From SE2 we consider the **replicability** as an important factor for the choice of the pilot building. This means that the building could act as an example to generate a systematisation in similar buildings in terms of use, construction characteristics or size, among others.

Interesting examples of where to act at a public level would be those that are repeated in cities, such as: social housing, schools or universities, hospitals, health centres, clinics, sports facilities, cultural or association centres.

The dissemination of this type of intervention tends to have a greater impact on society due to the public aspect and the fact that these are spaces of joint enjoyment or community value.

9.1. General recommendations

9.1.1. Location

It's recommended to be in a built-up area, with housing or other buildings nearby, but not in the city centre with high density, due to the safety considerations and the occlusions.

It is recommended to check the related regulations to ensure that the district is allowed to fly drones.

9.1.2. Type of building

Piraeus: According to the Grant Agreement it should be a municipal building. With low restriction in terms of accessibility (for complementing the data acquisition in case of being necessary)

Mostostal: Building under construction (SE1) and new building (SE2)

9.1.3. Characteristics of the building. Location

Building located in a block or solitary, both options are useful. In the case of being located next to other buildings, try to keep most of the facades free. Keep in mind that the more facades we can capture, the more information we will obtain. The façades that are not visible will not be captured and will be needed some external interpretation.

9.1.4. Characteristics of the building. Floors

A building with between 4-7 floors is recommended.

If the lower level of the building (e.g. 1-3rd floors) has some occlusion, the ground-based short-range scanner should also be applied.

9.1.5. Obstacles around the building

The environment should be "easy to fly". The intention is to make a detailed flight of the façade, the drone must fly close to it and capturing perpendicularly, so the trajectory is parallel to the façades and if there is any impediment, it makes the flight very difficult.

9.1.5.1. Vegetation

There could be vegetation nearby, but if this vegetation is near to the façade there is a probability of not capturing properly the area. So, the vegetation needs to be around 8-10 meters away at least.

9.1.5.2. Cables

The drone has a good system for automatic obstacle avoidance, but sometimes it may not detect cables on the street, so it is highly recommended that the environment does not have thin hanging elements. In case of having, the pilot needs to check its viability.

9.1.5.3. Antennas on the building

If the building has antennas on the roof, the total height of the building is counted up to the antenna, so the drone flight height starts from the antenna. This means that if the drone flies higher and further away from the building, we will get worse resolution and definition. A building without high elements on the roof is preferable.

9.2. Thermal recommendations:

9.2.1. Nearby surroundings of the building

The building may be located in a street area or in a square or park, it is not something that will hinder the flight. Different situations could affect the flight protocol (road closures, pedestrian control, change of bus line... depending on the regulations of the country/city). The choice of the surrounding environment is not a requirement, but for guidance one of the following options could be considered:

9.2.2. Building in an urban area without green areas around

Here the impact of buildings and roads on the behaviour of the building can be observed. In addition, if the streets are narrow, the situation would also be different than in a place with wide streets.

9.2.3. Building located in a square without much vegetation.

Here the impact of a large open space on the building on one of its façades and the difference with respect to the others that are surrounded by other buildings or streets can be observed.

9.2.4. Building close to a park/green area:

The impact of large green areas on the behaviour of the building envelope will be observed and can also be compared with façades close to streets or buildings.

9.2.5. Situations of restricted areas for drone flights

It should be considered that in some parts of the airspace drone flight is not allowed, restricted areas should be avoided in close proximity.

10. Annex B: Digital Twin Technical Requirements for data collection

This annex outlines the technical specifications and requirements for the tender of LiDAR scanning services, focusing on both drone reconstruction for outdoor areas and mobile mapping reconstruction for indoor environments. The project aims to create an integrated, comprehensive digital model of the targeted structure by combining both indoor and outdoor data for two services, which are SE1 Digital Twin Generation and SE2 Digital Twin Enrichment.

Section 10.1 refers to the technical requirements for the external and interior scanning. Section 10.2 and Section 10.3 elaborate the service details of SE1 and SE2. The proposal's utility, specifically whether it enables service providers for SE1 and SE2 to effectively perform their designated services, serves as a critical benchmark in evaluating the contractor's proficiency and competence.

The specific requirements are summarized:

- **Summary of required data set:**

Point cluster should include XYZRGBt information:

1. Geo-location Data (XYZ) (for both indoor and outdoor): Utilizing EGNSS (European Global Navigation Satellite System) for precise geo-referencing.
2. RGB Information (RGB) (for both indoor and outdoor): Colour mapping on the point cloud for realistic texture and detail.
3. Thermal Information (t) (only outdoor is required): Thermal imaging for identifying thermal patterns and insulation issues.

- **Summary of required scanning scope and solution:**

Table 7 Summary of required scanning scope and solution

	Exterior		Interior
Equipment	UAV (Drone with dual camera RGB + thermal)	SLAM (Laser scanner)	SLAM (Laser scanner)
Area captured	External walls Roof Immediate surroundings	Ground	Entire space

10.1. Technical requirements

10.1.1. Technical requirements for external flight

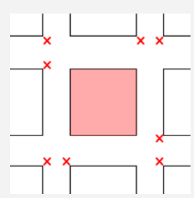
10.1.1.1. Equipment

Drone equipped with EGNSS information (or equivalent data can be converted to EGNSS coordination), terrestrial laser scanner, dual camera (RGB + thermal). It is also recommended to use a RTK during the flight to support the 3D reconstruction.

Table 8. Drone equipment recommended

	Laser Scan Sensor	Thermal Camera	RGB Camera
Minimum Accuracy (Laser Scan Senser) Minimum Resolution (dual camera RGB + thermal)	Centimetre (5 mm to 1 cm) to millimetre accuracy if equipped with terrestrial laser scanners.	640*512 pixels	12 Mpixels

Table 9. Examples of TLS equipment and drones that fit the requirements: NavVIS VLX-3 (NavVis), DJI MAVIC 3T or DJI MATRICE 30

GPS Information (EGNSS)	RTK + at least 4 georeferenced corners (centimetric accuracy around 1-3 cm) and if its possible 1-2 points in the building (roof) to scale properly the model. IT is also recommended to included points between the previous one for checking the accuracy of the model. All the points should be obtained with static GPS solutions. 		
Temperature Resolution		Around 2ºC	-
Camera focal length		-	Around 20 mm could be fine

10.1.1.2. Data collection

- Distance

The resolution of the image depends on the distance between the drone and the building, this ratio is called GSD (Ground Sample Distance). In this link you have a free tool to calculate this distance according to the building https://support.pix4d.com/hc/en-us/articles/202560249-TOOLS-GSD-calculator. The resolution, and thus, the distance of capturing will allow to identify thermal anomalies along the envelope.

- TLS Scanning
    - Scanner Positioning:

Position the scanner at a distance that ensures the laser can capture the façade with the desired resolution. This is typically a range of 5 to 50 meters, depending on the scanner's specification.

- Overlap of each scan:

The overlap of at least 20-30% is required between consecutive scans to provide enough common data points for accurate registration. The overlap may need to be increased for complex geometries or when scanning intricate details.

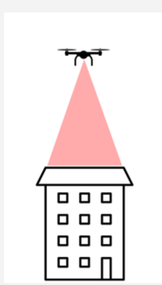
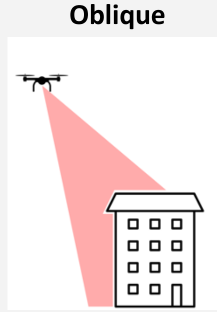
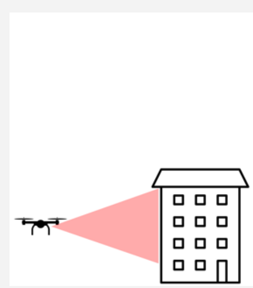
- Scanning Strategy:

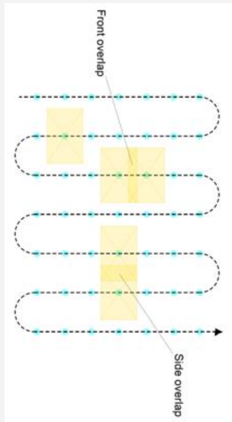
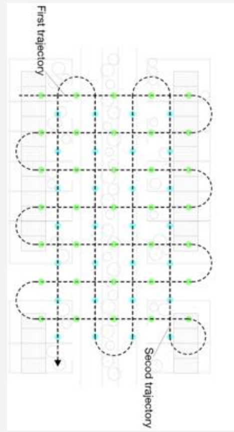
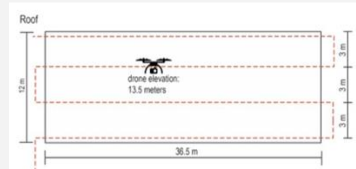
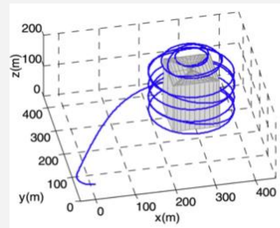
Conduct a grid-based approach by dividing the façade into sections that each scan will cover, considering the overlap. Use a consistent pattern for scanning, such as top to bottom and left to right, to maintain organization.

- Flight type and characteristics

Vertical, oblique and horizontal flights must be necessary to capture in detail the entirety of the building's facades.

Table 10. Flight type and characteristics

Flight	**Vertical**	**Oblique**	**Horizontal**
			

Trajectory	 **Grid**	 **Double Grid**	 **Zig-zag**  **Ring**
Camera position	90º	30º - 45º	0º - 30º
Image Overlay (calculated with respect to the thermal camera GSD)	70% - 80%	70% - 80%	>80%
Point Cloud	For point detection in the point cloud, each point must appear in at least 4 images.		

- Best time to fly: it is important to carry out the flight fast. This is due to the influence of the sun in the thermal data.

Table 11. Best time to fly

	Summer	Winter
Sky	Cloudy (avoid shadows)	Cloudy (avoid shadows)
Timetable	Evening (after sunset)	Morning (before the sun rises)

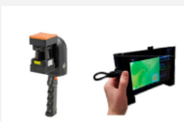
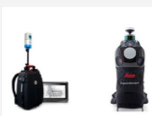
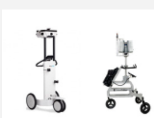
10.1.1.3. EGNSS data integration

The integration of European Global Navigation Satellite System (EGNSS) data into LiDAR scanning workflows necessitates adherence to stringent technical requirements to ensure high precision and accuracy in geospatial datasets. The data acquisition needs to be complemented with a GNNS receiver (or equivalent receiver) that is compatible with EGNSS services, such as Galileo, to provide robust satellite coverage and signal integrity for geo-referencing. The positional accuracy of the integrated system should meet the project's specifications, often requiring real-time kinematic (RTK) positioning to achieve centimeter-level precision.

10.1.2. Technical requirements for indoor scanning

10.1.2.1. Equipment

Table 12. Laser Scan Sensor – Mobile Mapping

Sensor Type	Weight (dimensions)	Accuracy	Range/Speed
 **Portable**	Low	Centimetric (1-3 cm)	Around 30-50 m / 500,000 points per second
 **Backpack**	Middle	Centimetric (5mm-2 cm)	Around 50-100 m/ 500,000-1,000,000 points per second
 **Wheelbarrow**	High	Centimeter (5 mm to 1 cm) to millimeter accuracy if equipped with terrestrial laser scanners.	Around 80 m / 100,000 points per second

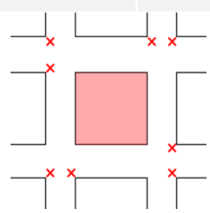
10.1.2.2. Data collection

- Avoid the presence of people and make sure that the scanning route is free of obstacles (open doors).
- The walking speed must be constant.
- Acquire the data by using closing loops: the start and end points should be the same.
- Each time you scan a room, you need to follow a closed-loop protocol, as shown in the Figure 63.

Figure 63. Data collection for indoor scanning: following close-loop protocol for each room scanning

- Integration with the drone flight: it is recommended to acquire an overlap area between the drone and the indoor mapping in other to align both data sources. In this sense the indoor mapping should take some information from the external envelope. For example, the indoor mapping could acquire the entrance/s of the building. The overlap between the UAV and indoor mappings should be 30%. The alignment could be also carried by targets, in this sense this target could be detected by the drone and the indoor mapping (i.e. planar targets). These targets should be georeferenced coordinates. The minimum number of targets should be 6-8.

Coordinate system	ETRS89 / UTM



10.2. Service details of SE1 – Digital Twin Generation

A Digital Twin is a digital replica of a physical entity, system, or process. In the context of the project, the digital twin model accurately reflects both the indoor and outdoor elements of a building, based on point clusters, providing the building level geometric and spatial relationship information. The base Digital Twin sheds the light on the further model semantic enrichment through IoT data or energy consumption data. The digital twin can also offer real-time operational insights and advanced predictive analysis.

10.2.1. Working mechanism of digital twin generation

The main part of generation workflow of digital twin generation is the web-based Converter. As shown in below diagram (Figure 64), the workflow begins by taking the processed point cloud data collected from LiDAR scans or photogrammetry as its input. The raw data shall be processed into registered point with acceptable noise that represent the surfaces of scanned objects.

10.2.1.1. Required Data input is summarized:

Point cluster should include XYZRGBt information:

1. Geo-location Data (XYZ): Utilizing EGNSS (European Global Navigation Satellite System) for precise geo-referencing.
2. RGB Information (RGB): Colour mapping on the point cloud for realistic texture and detail.
3. Thermal Information (t): Thermal imaging for identifying thermal patterns and insulation issues.

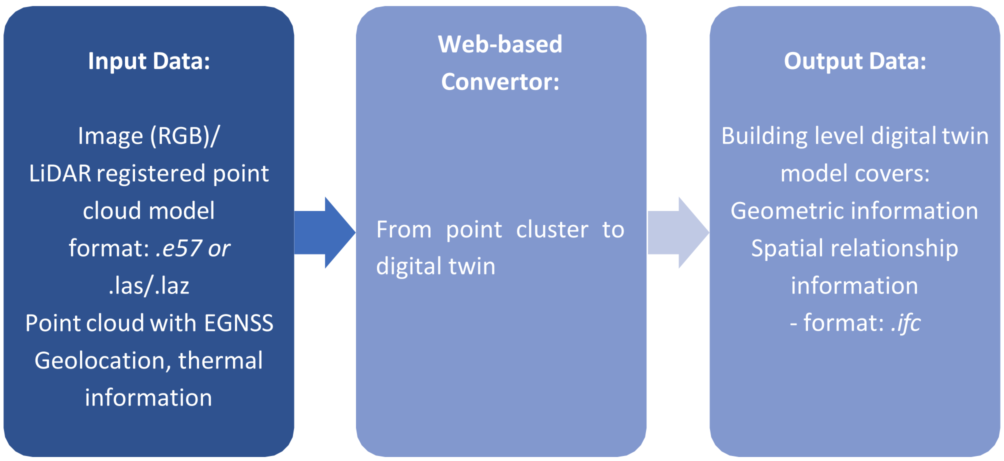


Figure 64. Workflow for Digital Twin generation

Leveraging advanced machine learning algorithms, the converter applies automated segmentation to this data, effectively categorizing the multitude of points into distinct clusters, each corresponding to individual building elements like walls, floors, ceilings, etc.

Once the point cloud data is segmented, the converter then translates these point clusters into a set of Industry Foundation Classes (IFC)[4] objects. These IFC objects as the output data represent. The generated Digital Twin of the scanned building is a three-dimensional digital representation that maintains both the geometric and spatial characteristics of the building. This conversion process is guided by both geometric properties and the spatial relationship information inherent in the point clusters, ensuring that the 3D structure and layout of the original building are accurately represented in the IFC objects. The results of the generated digital twin model will be visualised through a web-based application and can be associated with VR/AR devices providing the immersive experience for users.

10.2.2. Working efficiency

The speed of automatic Digital Twin generation from registered point clusters is heavily dependent on a variety of factors, including the complexity and size of the point cloud data, the efficiency of the

[4] https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/

segmentation and conversion algorithms, and the computational resources available for processing. For large and complex point cloud data, the segmentation and conversion processes could be computationally intensive and thus, could take a substantial amount of time. However, advances in machine learning and parallel processing techniques have significantly improved the efficiency of these processes, reducing the time required. For one of the research projects that the UOC team completed in the past, for a model with one-kilometre railway point cloud model of 20GB, it took about 8 minutes to generate the digital twin model automatically.

Despite the computational complexity of the task, the system is designed to generate Digital Twins as quickly as possible without sacrificing the quality or accuracy of the models. As technology and algorithms improve, the speed of Digital Twin generation is expected to continue increasing, further reducing the time between data upload and Digital Twin availability.

10.2.3. Equipment for DT visualisation

The equipment Virtualizer will be used in the project to test generated digital twins. The basic information and manual are attached.

Table 13. Equipment details

Equipment details	
Brand	Cyberith Virtualizer
Model	Virtualizer Elite 2
Software (provide details of required software, dongles to operate, etc.)	https://www.cyberith.com/virtualizer-elite/
Accessories	VR headset: HTC Vive Pro Eye

Table 14. Available documents

Available documents	
Manual	Available here and here
Training Material	No Virtualizer User Instructions: https://www.youtube.com/watch?v=4ycatcSndng Virtualizer Features: https://www.youtube.com/watch?v=q_rv-213Ijl

Pen Drive / CD	No
Description	The Virtualizer ELITE 2, consisting of the mechanical construction for locomotion in virtual reality as well as the integrated sensor system for detecting the movement of walking, rotation and the user's vertical motion. Overhead cable management system and HMD mount ("The Arm"). Software Development Kit for Windows, Plugins for Unity and Unreal Engines and testing applications. Virtual Trainer example: https://www.youtube.com/watch?v=NhMBj8uXX9k

10.2.4. Digital Twin Generation

Automatic generation of a Digital Twin involves leveraging its tessellation-type as-is geometry generation and the object spatial relationship representation. In the end, the generated digital twin model will be tested and verified under the VR/AR environment.

10.2.4.1. Digital Twin generation based on the registered point cloud

The data sources for the digital twin generation contains the registered point cloud cluster, visuals and thermal images and the EGNSS data. The multiple information will be integrated based on a unified coordination system. The generated digital twin model has the potential to be shown in the web-based viewer (see Figure 65). The spatial relationship among the objects will be visible through this method.

Figure 65. Demonstration of 3D visualization of building (Developer's Guide | Viewer | Autodesk Platform Services

10.2.4.2. Identification of building object attribute and spatial relationships

Each element within the Digital Twin carries certain attributes that define its properties, such as type and family of the element, size, position, or spatial relationship in the case of appliances (see Figure 66).

Identifying and understanding these attributes are critical for numerous analyses and decisions. For example, the area of a window can impact the building's thermal performance. Accurate data about these attributes enables more precise simulations and analyses, leading to better informed decisions and more efficient building performance.

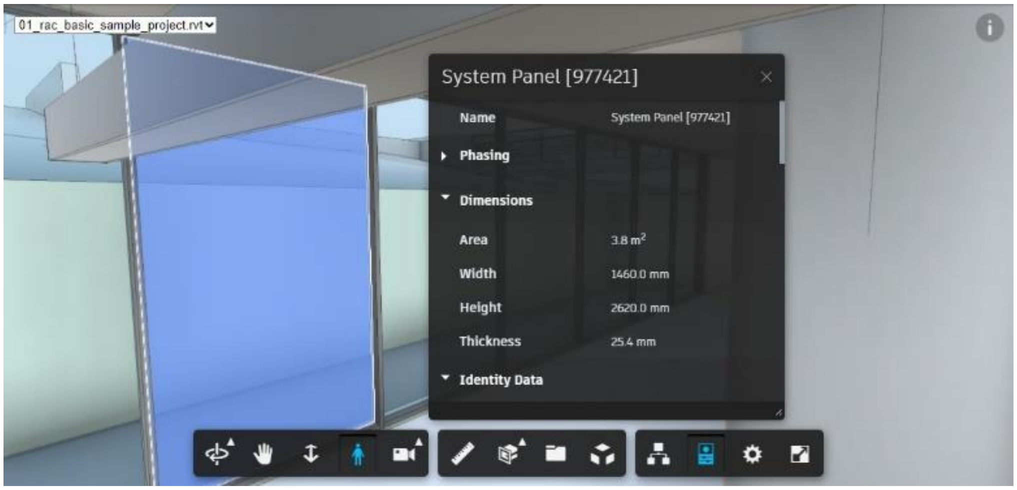


Figure 66. Demonstration of building element attribute exhibition (Developer's Guide | Viewer | Autodesk Platform Services)

10.2.4.3. Walkthrough in virtual building environment through AR/VR technologies

One of the most valuable aspects of a Digital Twin is the ability to navigate or walkthrough the virtual building environment from a human perspective (see Figure 67) in the mixed reality environments (see Figure 70). This not only provides an understanding of the layout and spatial relationships but also creates an immersive experience that can help in identifying design flaws, understanding user experience, or presenting the building plan to stakeholders. Users can navigate through the building just like they would in real life, examining each area from different angles and perspectives.

Figure 67. Demonstration of 3D visualization of building (Developer's Guide | Viewer | Autodesk Platform Services)

Figure 68. Digital Twin visualization through mixed reality environment (Staff and students | Construction Information Technology Laboratory (cam.ac.uk)

10.2.5. Potential of Digital Twins for energy analysis

The generated Digital Twin provides a comprehensive understanding of the building's spatial and geometric aspects, offering a solid foundation for further energy-related analyses. It is not merely a 3D model, but a detailed representation of the physical world that can provide insights into how a building's structure and layout might impact its energy usage. For example, the geometric configuration of a building can significantly influence its energy use - such as the positioning of windows impacting sunlight exposure, or the arrangement of rooms affecting heating requirements. Similarly, the Digital Twin can help identify spatial relationships that might contribute to energy inefficiencies. The potential values of created digital twin are listed below:

1. Insights into Building Geometry: Understanding the geometry of a building is fundamental to energy analysis. The size and shape of the building, the thickness of walls, the placement and size of windows, and the ceiling height, can all have a substantial impact on energy usage. These factors influence how heat and light move through the building. For instance, larger windows can let in more natural light, reducing the need for artificial lighting, but may also lead to more heat loss in winter and heat gain in summer. With a detailed Digital Twin, users can understand these geometric factors more accurately, leading to more precise energy simulations.
2. Understanding Spatial Relationships: The layout of a building can also significantly affect energy consumption. The arrangement of rooms, their proximity to each other, and their exposure to external elements, like sunlight or wind, can affect heating, cooling, and lighting needs. By analysing these spatial relationships in a Digital Twin, users can identify areas where energy efficiency may be improved. For instance, rooms that receive ample sunlight could be used more during the day to reduce artificial lighting needs.
3. Further digital twin enhancement: in the SE2, the digital twin with sufficient geometry and spatial relationship information shall be enhanced with the relevant energy-related information attached to certain building elements. This information might be the green building attribute to building

elements, or real-time data from IoT sensors. This could allow for more precise simulations, real-time energy monitoring, predictive maintenance of HVAC systems, and other advanced features

10.3. Service details of SE2 – Digital Twin Enrichment

The following guide has the aim of summarizing the main aspects related with the Digital Twin enrichment of the project BUILDSPACE**.** These aspects are in line with the user requirements of the project (Table 15).

Table 15. Relation between the user requirements and the outputs of the DT enrichment

Related User Requirement	Specification Description	Specification Details	Type
RQ03	Visualise the building's energy efficiency rating.	SE-2 (DT enrichment) could provide valuable information about the presence of thermal anomalies along the building's envelope. To this end it is required to fly a DRONE equipped with a RGB camera and a thermal camera to capture a set of images from which it will be possible to generate the final 3D model. Additionally, this flight needs to be supported by GPS points to scale and georeferenced the data.	Data collection and storage. Visualisation, model development
RQ15	Visual representation of the progress of construction works on a daily/weekly basis.	SE-2 (DT enrichment) could help with this requirement. In this sense it requires a survey with a Mobile Mapping Solution that can provide a 3D point cloud of the real state of the construction. This 3D point cloud could be captured at different stages of the building and then compared.	Data collection and storage. Visualisation
RQ18	Visual identification of thermal bridges of the buildings.	SE-2 (DT enrichment) could provide valuable information about the presence of thermal anomalies along the building's envelope. To this end it is required to fly a DRONE equipped with a RGB camera and a thermal camera to capture a set of images from which it will be possible to generate the final 3D model. Additionally, this flight	Visualisation

		needs to be supported by GPS points to scale and georeferenced the data	
RQ19	Detect cracks in the building structure or displacement of the building or surrounding buildings.	SE-2 (DT enrichment) could provide valuable information about the anomalies of the envelope by using high quality 3D models with RGB information.	Visualisation, usability, model development

Under the basis of the user requirements, we recommended the use of the following digitalization technologies:

- For outdoor mapping: aerial photogrammetry. In this case is required the use of a drone equipped with an RGB camera (and a thermal camera if thermal information is required) as well as a GPS sensor to georeferenced the information and scale it. Both aspects are detailed in Section 2.
- For indoor mapping: it is recommended the use of mobile mapping solutions based on the use of the SLAM approach. In this case it is necessary a mobile mapping laser scanner to capture the data. It is possible to capture RGB information by using cameras that are included in this sensor.

10.3.1. Drone reconstruction (outdoor)

This section will summarise the basic questions related with the 3D digitization of buildings by using drones. More specifically we recommended the use of a drone equipped with an RGB and a thermal camera since they can capture the reality (for 3D reconstruction) as well as the superficial temperature of the envelope. Both aspects are detailed in the following sections.

10.3.1.1. Applications

There are many applications for this service. Overlaying different information images (in this case RGB and thermal images) on a 3D model, we can provide new insights and ways to improve or make better use of existing buildings.

Here are some of the possible applications related to the project:

- To detect anomalies in the building envelope.

Presence of thermal bridges caused by deterioration of materials, poor sealing of elements, air or water infiltration, etc.

Figure 69. Façade of a building

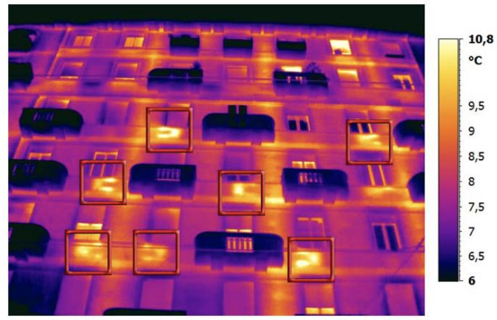


Figure 70. Detail of temperature distribution on the upper part of the facade. In the red squares, the warmer areas due to the heat flux generated by the heaters (You Hou et at, 2022)

- To detect anomalies in the structure or internal systems (plumbing, electricity, heating system, etc.) of the buildings.

For example, the presence of internal cracks that are not being observed, internal leaks in pipes, malfunctioning in the electrical systems.

It could be used in normal situations or in situations of natural disasters or catastrophes.

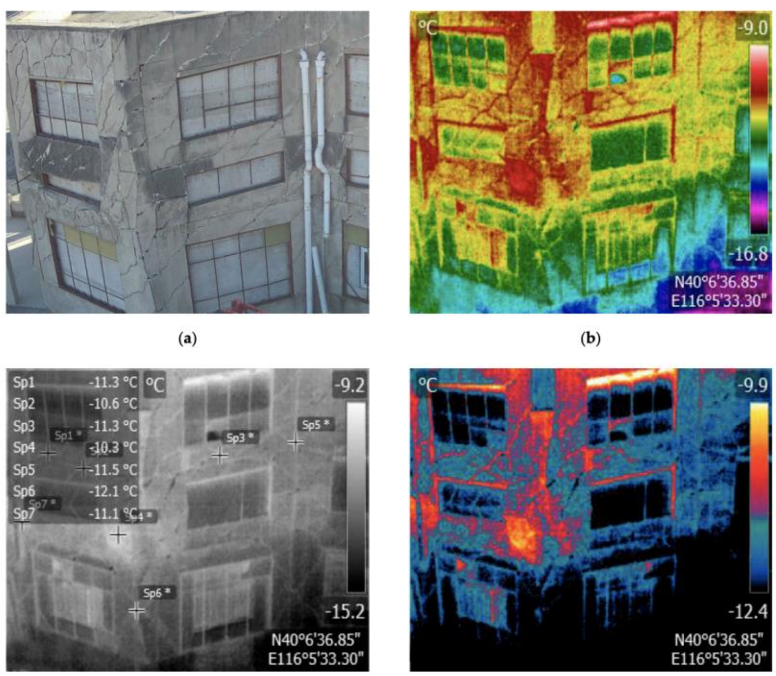


Figure 71. Thermal infrared image detection result of building wall cracks after earthquake. (a) Visible image; (b) ingrained thermal image; © grayimage and crack mark point temperature; © crack extraction result (Zhang et al, 2020)

- To detect the efficiency of buildings and their envelopes at the level of home, building, neighbourhood, city, or even country.

This helps to identify which buildings or neighbourhoods need intervention.

Also, measures could be taken, not only at the building or home scale, but also to carry out improvement or rehabilitation plans for larger areas.

Figure 72. Thermal image of a neighbourhood. Benedette Cuffari, M.Sc., 2016

- To detect heat islands and be able to intervene in them.

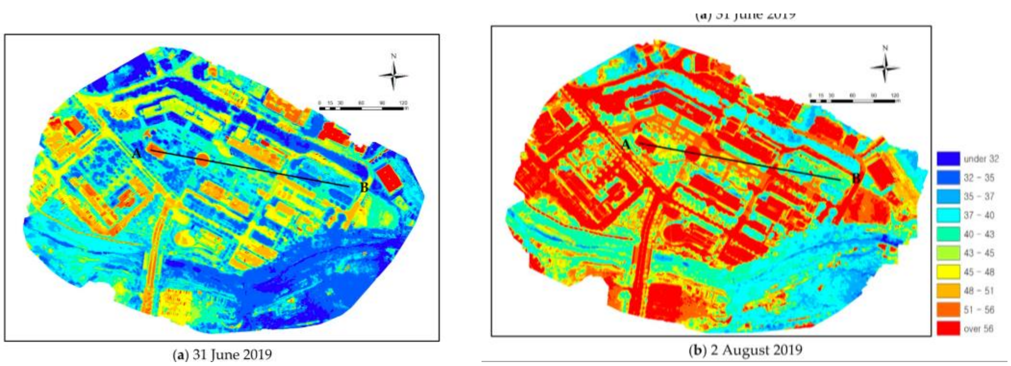


Figure 73. Thermal image of a neighbourhood. Benedette Cuffari, M.Sc., 2016

- To detect anomalies in the operation of photovoltaic systems.

Thermal imaging is useful for detecting cells that are not working properly, or panels that are not providing what they should.

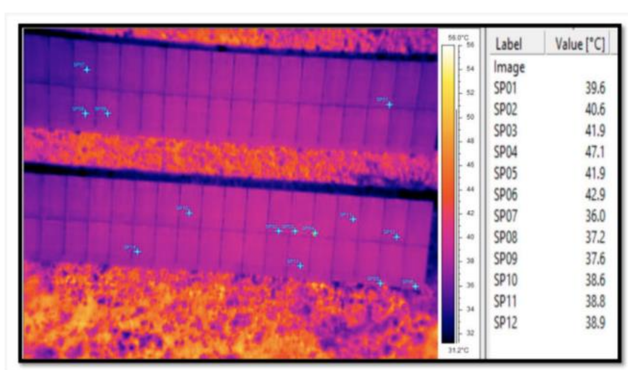


Figure 74. Temperature of hotspots of the thermal image. Pruthviraj, U., 2023

- To have more knowledge about building conditions to decide where to invest, where to locate a business, where to buy a house, etc.

10.3.1.2. Technical requirements (hardware)

For the flights a drone equipped with a thermal and a RGB camera (dual camera) is required. Generally, drones with thermal cameras have a visible camera next to it. The next lines detail the technical specifications:

- Thermal camera:
    - Minimum resolution: 640*512 pixels
    - It is recommended to use any GPS information within the metadata for position. This information could be obtained by using an RTK module (more detailed in the drone section showed below).
    - Accuracy of the temperature: around 2 °C
- RGB camera:
    - Resolution: at least 12 Mpixel resolution
    - It is recommended to use any GPS information within the metadata for position. This information could be obtained by using an RTK module (more detailed in the drone section below).
    - Regarding the focal length of the camera: it is recommended a length that covers the interest area during the flight (around 20 mm could be fine).

Under this basis we propose the use of the following DJI drones (famous type of drones). In this context there are two types of drones:

- DJI MAVIC 3T: practical drone with a reduced cost in comparison with the other. In case of choosing this drone, you need to consider:
    - Sensor to include: RTK sensor, RGB camera and thermal camera.
    - Purchase cost: around 8.000€
    - Rating cost (company service-data capturing): around 1000-1500 €, including GPS points.
- DJI MATRICE 300: high-end drone
    - Sensor to include: RTK sensor, thermal camera (H20T)
    - Purchase cost: 15.000€ drone plus around 10.000€ thermal camera.
    - Rating cost (company service-data capturing): around 2000 €, including GPS points.

Aspects related with the GPS coordinates: it is recommended the use of a drone with RTK sensor as well as some points (around 8 points at different positions of the building) to scale and georeference the model. The first one will provide geoposition of the images during the flight and the second one will provide the geoposition of specific points (generally corners or other singular points) that will be used during the processing of the models to create the final one.

Regarding the hardware specifications it is required (in case of processing the data in the computer and not in cloud applications):

- Dedicated GPU: NVIDIA or AMD GPU with 4-6Gb. We recommended, for previous experiences, NVIDIA cards.
- CPU: 4 - 12 core Intel (i7-i9), AMD or Apple M1/M2 processor, 2.0+ GHz
- RAM: 16 Gb (minimum), 32 Gb (recommended)

Here some examples of computers able to process this type of data:

- Personal computer: MSI Crosshair 17 C12VF-264XES Intel Core i7-12650H/32GB/1TB SSD/RTX 4060/17.3". Around 1400 €.
- Computer: MSI MAG Infinite S3 13TC-657XES Intel Core i7-13700F/16GB/1TB SSD/RTX 3060. Around 1200 €.

10.3.1.3. Legal issues and operator qualification questions

Use of a drone requires, at least in Europe, to have a qualified pilot. This pilot needs to pass an exam that qualifies him for the use of drones. Apart from this, this type of operation requires to have a legal "company" for flight the drone with civil insurances.

This "company" is a UAV operator and must be registered with the airspace regulator in the operating EU country. The operator of each member country can fly in other EU countries if it complies with the legislation of each EU member country. In addition:

- The registered operator must have approved city-scenario specific works, documentation and mitigation means required by the country in which it flies.
- Cover liability insurance.
- Have pilots trained and qualified in the required scenarios.
- Make flight requests in accordance with the legislation of the country of flight.
- Pay any local taxes for the flying area.
- Obtain permissions from the owners of the object to be flown.

These issues frame the flight of a drone as a specialized service. For this reason, we recommend contracting a drone company to perform the flight. In this case the company will cover the data acquisition (including the GPS information) as well as the permission for performing the flight. IMPORTANT NOTE: since the drone takes images, there are some issues related with the privacy of the owners of the building.

So, before performing the flight, the contracted need to have the permission of the building for performing the flight during a specific hour and day.

10.3.1.4. Data capturing

The following section will expose the general recommendations for the drone flight:

- **The resolution of the image depends on the distance between the drone and the building**. In order words, there is a relation between the size of the pixel and the reality. This relation is named as GSD (Ground Sample Distance). For example, a GSD of 1 cm means that the pixel represents a squared areas which has a 1cm of side. This link leads to a free tool to compute this distance https://support.pix4d.com/hc/en-us/articles/202560249-TOOLS-GSD-calculator. With this tool it is possible to determine the work-distance for the drone (H-flight height). In this case it is required to introduce in the tool the data of the thermal camera (since is the worst one) and the tool will provide the GSD in accordance with a specific flight height. NOTE: the tool considers the flight height as vertical, but it could be used in the horizontal direction (façade mapping).

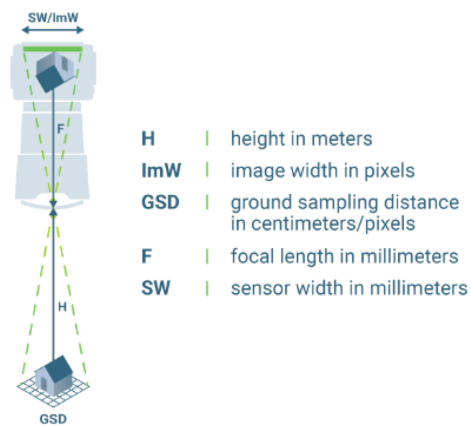


Figure 75. The concept of Ground Sample Distance

- **The success is on the overlap between the images**: the 3D reconstruction of an object (i.e., building) by photogrammetry (images) is based on taking images of the same area from different positions. For the 3D reconstruction it is required at least that they appear in four images. So, it is required to have a high overlap between images. This overlap is conditioned by the type of flight scheduling controlled by the drone application. There are two flight schedules:
    - Vertical and Oblique: Given the low resolution of thermal cameras, flight scheduling must be done based on the thermal camera.
        - If the UAV is capable of GNSS-RTK flight, overlaps of 75x75% may be feasible, although scale changes due to different depths and short distances may cause problems, it could be necessary to increase the overlaps to 80x80%.

- If the UAV doesn't have GNSS-RTK in flight, which is feasible when the drone is between buildings, the overlaps should be increased to 90x90%.

- Horizontal: The drone is placed on the facades and goes up and down them. The problem with this type of flight is the programming of the flight, see tools such as UGCS and the loss of GNSS-RTK signal.

Figure 76. Concept of overlap between images for the 3D reconstruction

- There are different paths in accordance with the purpose followed:

  - Flight planning in case of requiring a thermal/3D mapping of the roofs:
  - The trajectory to be followed will be the grid trajectory (Figure 77).
  - The minimum overlaps are between 75% (frontal) and at least 60% (lateral).
  - The camera position will be fully perpendicular pointing to the ground (zenith plane).
  - It is highly recommended the use of an RTK sensor as well as 6-8 GPS coordinate on the ground to georeference and scale the model.

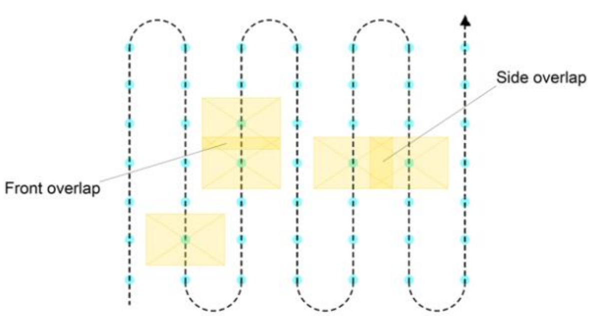


Figure 77. Proposal of roof flight. Own elaboration

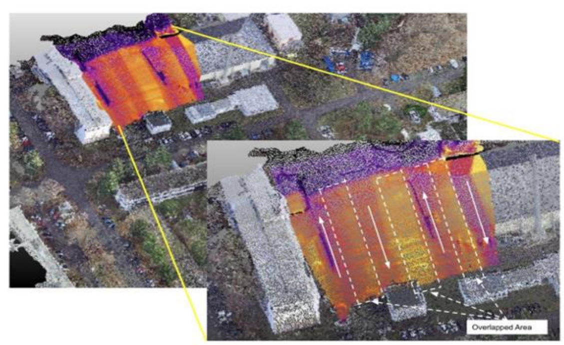


Figure 78. Yu Hou et al, 2022

- Flight planning of quarries and built-up areas

  - To generate both 2D and 3D reconstructions, it is essential to have several alternative viewpoints for each area.
  - Is necessary to complete a double grid trajectory, completing one trajectory as in the case of an orthophoto and continuing with another similar trajectory at 90

degrees (Figure 79). With this type of trajectory, we ensure that we have photographs from four (approximate) points (north, south, east and west).

- The overlap, as in the previous case, 75% and 60%.

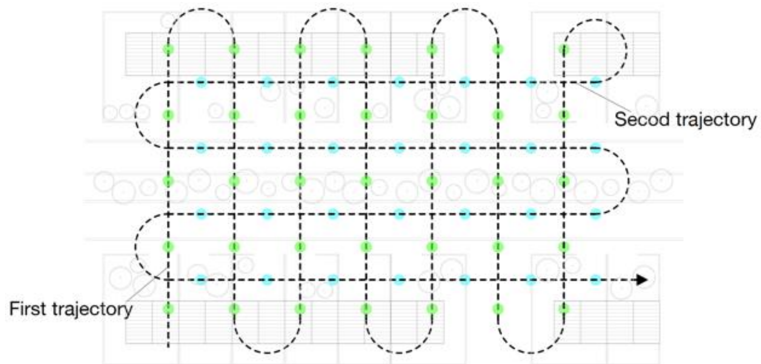


Figure 79. Proposal of flight path. Own elaboration

- Flight planning to generate 3d volumes (buildings)

  - This is the case with the most differences with respect to the previous ones. In this case, it is necessary to complete three circular trajectories at different heights, in a single flight or in several consecutive flights.
  - The camera must form an angle of 45º in the lowest trajectory, 30º in the middle trajectory and 10º in the highest trajectory.
  - It is necessary to take between 40 and 80 shots in each of the orbits, each photo must be separated from the previous one by 5º-10º degrees.
  - In the case of very large objects, it is necessary to modify these values so that there is still the same amount of overlap between images. In this case, more pictures, every fewer degree and if the object is very tall, progressively adding more orbits.
  - In all cases, the camera should take as the point of interest the approximate centre of the object.

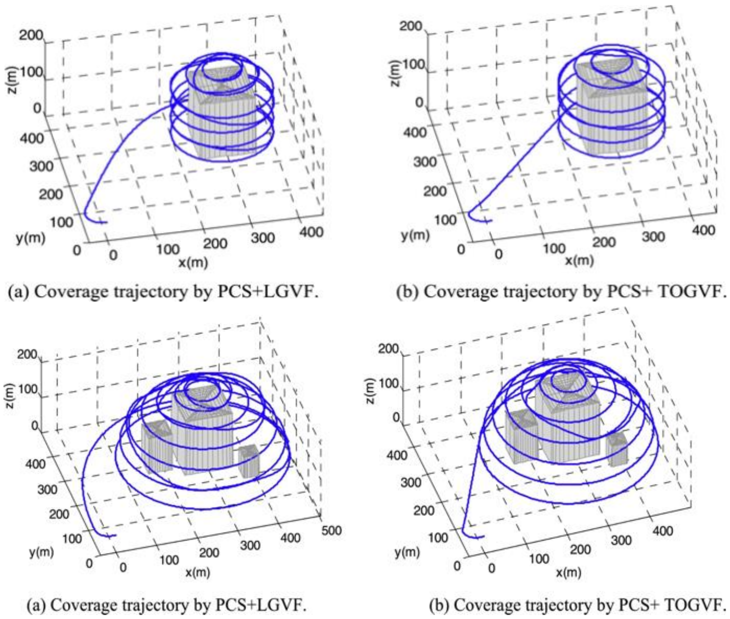


Figure 80. Peng Yao et al, 2019

- *For the vertical walls to be reconstructed (better quality than the previous one)*: the camera must be pointed at an angle of between 10º and 35ºwith respect to the building façade. The path is detailed bellow but requires an overlap between consecutive images of about 80% (use the GSD calculator for this purpose).

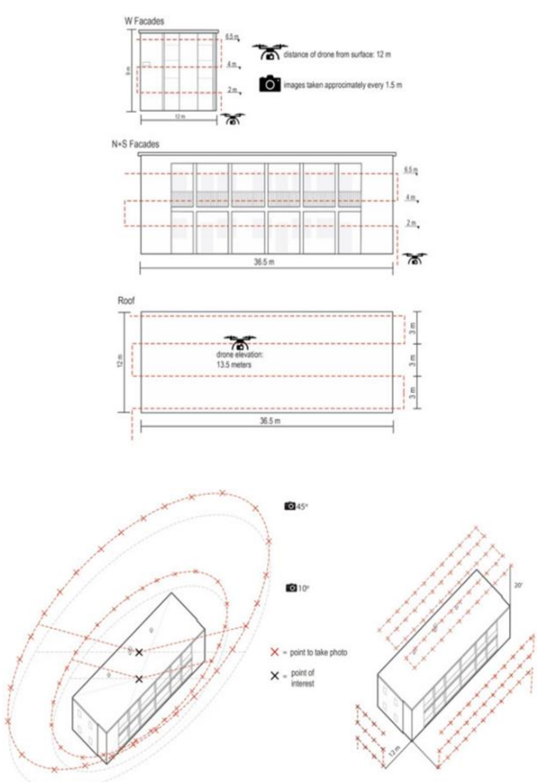


Figure 81. Data acquisition protocol. Adapted from: Rakha, T., & Gorodetsky, A. (2018)

- Best time to fly:

    - Weather: better conditions for thermal imaging and RGB are cloudy days (avoiding shadows). This will avoid overheating of surfaces and lower image contrast (easier to capture good images). Also, it's preferable to fly on less windy days, so you will have more stability in the drone and the results won't be affected.
    - Hours: In winter it's recommended to take thermal images in the morning, before the sun starts to warm up; or in the evening, when the sun has already disappeared. Ideally, the inside of the building should be warmer than the outside, so that heat loss (thermal bridges) can be better observed.
    - In summer, the time of capture would be at night, when the sun has stopped heating the surfaces and they start to radiate heat. In summer it is possible to detect the heat island.
    - Therefore, in winter the thermal bridges of the envelopes are more easily observable, and in summer, the urban heat islands.

- **Final remarks regarding the data acquisition:** it is recommended the acquisition of images in RAW format since they offer better results during the processing stage. Don't forget to take the RTK position during the flight (it is taken per image). This information makes the processing stage faster and more accurate.
- **Don't forget the GPS points**: it is mandatory to have GPS points (around the building and at different heights if possible) to scale and georeferenced the model with great accuracy. Even if the drone takes RTK positions.

10.3.1.5. Software for processing the data.

Nowadays there are different photogrammetric solutions able to pass from a set of 2D digital images to 3D point clouds. The most common are the following ones:

- Pix4D (https://www.pix4d.com):

    - Great integration between RGB and thermal imaging.
    - Great robustness, able to extract 3D point clouds and 3D meshes.
    - This software integrates flight planning in a app.
    - Great integration with DJI drones.
    - Could integrate 3D from photogrammetry (i.e., drone) and laser scanner (i.e., terrestrial laser scanner).
    - Able to integrate control and geo-referencing.
    - Cost: 4,000 €; cloud application 141 € per month.

- Agisoft Metashape (https://www.agisoft.com/):

  - Large set of tools for measuring, parallel processing
  - Great robustness, able to extract 3D point clouds and 3D meshes.
  - This software can calculate the flight based on a rough 3D model (downloaded from Google Maps)
  - Able to integrate control and geo-referencing.
  - Able to script in Python some additional functionalities.
  - This software could integrate 3D from photogrammetry (i.e., drone) and laser scanner (i.e., terrestrial laser scanner).
  - Cost: 3,500 €. Cloud processing 5€ per hour with possibility of storage of 100 Gb per 10 € (month).

- Reality capture

  - Better performance than the previous one
  - This software is not able to obtain 3D point clouds, just only 3D meshes.
  - We haven't found information about the integration of RGB and thermal imaging.
  - Able to integrate control and geo-referencing.
  - Pay per service. You only pay in accordance with the size of your project as well as when the results fit your purpose (10€ per project approximately). 3,500 € for a permanent licence

- Drone Deploy

  - All-in-one application also integrates 360º images for monitoring constructions. This app includes acquisition, processing and analysis.
  - It includes thermal and RGB processing.
  - Cloud services 600€ per month.

Most of the software is able to provide the 3D point cloud (except for Reality Capture). However, it is possible to pass from the 3D mesh to the 3D point cloud by using the open-source software CloudCompare ® (https://www.danielgm.net/cc/).

10.3.2. Mobile mapping reconstruction (indoor)

10.3.2.1. Applications

The use of this type of sensor strongly reduces the capture time (requiring 75% in comparison with traditional methods) as well as reducing the investment (25% less).

10.3.2.2. Technical requirements (hardware)

Nowadays there are a plethora of sensors for indoor mapping while the user is in movement. These sensors could be classified in three categories (Figure 82). The type of sensor depends on the type of environment to scan (Figure 83).

Figure 82. Different types of mobile mapping solutions for indoor scanning.

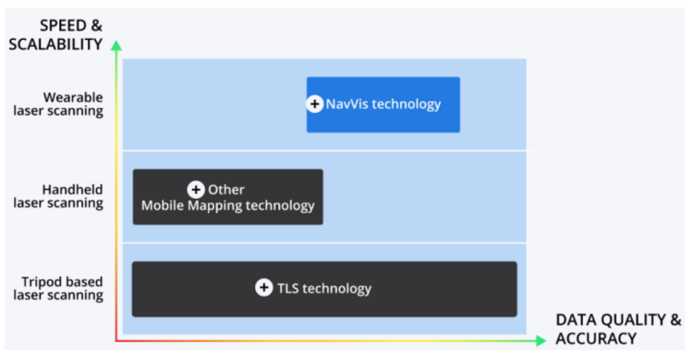


Figure 83. Comparison in terms of speed and accuracy of the three types of scanners. Adapted from: https://www.navvis.com/pricing

The following Table 16 reports a general comparison of these values, which are based on the publication "Mobile indoor mapping technologies: A review", Roi Otero, Susana Lagüela, Iván Garrido, Pedro Arias (https://doi.org/10.1016/j.autcon.2020.103399).

Table 16. Comparison of mobile indoor mapping systems

Type of sensor	Weight (dimensions)	Accuracy	Range/ Speed	Data processing
Handheld	Low (reduced). Could be equipped by a unique operator	Centimetric (1-3 cm)	Around 30-50 m / 500,000 points per second	It is possible to obtain data in real time. However, some post-processing work is

				required to improve the final quality
Backpack	Medium (medium). Could be equipped by an operator. However, the dimension of the equipment makes the mapping of narrow spaces difficult. It is recommended for mapping large scenarios since they are equipped in the back.	Centimetric (5mm-2 cm)	Around 50-100 m/ 500,000-1.000.000 points per second	It is possible to check the data in the field. However, it is required some post-processing work to improve the final quality
Trolley	High (high). This type of sensor is less portable. It is difficult to scan different floors because of stairs.	Centimetric (5 mm to 1 cm) to millimetric accuracy if they are equipped with terrestrial laser scanners	Around 80 m / 100,000 points per second	Requires the post-processing in office

Under this basis we recommend the following commercial sensors:

- Zeb Revo (GeoSLAM): this handheld laser scanner is commonly used in digitalization. It is highly portable and robust and integrates RGB data and 360º images.
    - Purchase cost: 50,000 €
    - Renting cost: 500 € per day. You can map an entire building in a day.
- NavVIS VLX-3 (NavVis): this is a trolley solution able to provide 6 mm accuracy approximately.
    - Purchase cost: 90,000 €
    - Renting cost not found.
- Faro Focus Swift (Faro): this mobile system is the most accurate one. It can provide millimetric accuracy since it integrates a static laser scanner.
    - Purchase cost: 90,000 €

Regarding the computer requirements we could consider the same specifications that those showed in Section 10.1.

10.3.2.3. Legal issues and operator qualification

No licence is required for using this type of sensor. The data acquisition is relatively easy, requiring to consider only some specifications (for more details see the next section).

10.3.2.4. Data capturing

The data capturing with this sensor requires to take into consideration the following:

- Acquire the data without people (if possible) and with all the doors open. In other words: create an environment on which you can walk with the sensor in a continuous way.
- The walking speed should be constant and like a walk speed.
- Acquire the data by using closed loops: the starting and the ending points should be the same. Additionally, each time you scan a room you need to follow a close loop protocol as the figure 16 shows.
- Take GPS positions**:** in line with the drone flights. It is required the acquisition of 6-8 GPS points (to georeferenced the data). Since is an indoor mapping the GPS information need to be taken outdoor. Ideally placed as the GPS points for the drone flight. Thanks to this it will be possible to place in the same environment the drone and the indoor 3d models.

Figure 84. Example of a mobile mapping path. Adapted from: Di Filippo, 1897

10.3.2.5. Software for processing the data.

There is not a general software for processing this type of data. In this case the user needs to process the data by using the manufacturer’s software. Anyway, the output of these sensors must be one of these formats to process it in other non-proprietary software:

- XYZ/PTX/PTS (less recommended due to the low compression ratio)
- OBJ/PLY
- LAS/LAZ (this extension works well with georeferenced data)
- E57 (highly recommended due to the high compression ratio)
- RCS/RCP (this format is recommended in case of using Autodesk applications)

10.3.3. Integration of indoor and outdoor data

Once both 3D point clouds (indoor and outdoor) have been obtained it is required to register both in the same coordinate system (this is not required in case of having georeferenced data in both point clouds). To this end we recommend the use of the open-software solution CloudCompare® (https://www.cloudcompare.org/main.html). This software integrates two options for registering point clouds:

1. Based on GPS points: previous sections highlight the necessity of using GPS information for the drone and SLAM mapping. It is mandatory for the first one, but for the second one is only recommended since it allows a direct position of the data in the same coordinate system (see the table below).
2. Based on overlap areas: in this case it requires the indoor and outdoor point clouds. It is recommended that both point clouds have a 20% of overlap between them (common area). In this case the workflow is the following one:
    - Rough alignment: during this stage the user needs to identify three common points (i.e., squares, windows, etc.) between the indoor and outdoor point clouds.
    - Fine alignment: this stage is made in an automatic way. In this case the computer, based on the three points previously identified, overlaps the common areas by minimising the distance between common points (on the overlap areas).
3. Based on artificial targets: there is another option to register both point clouds. The option is target-based. In this case it is required, during the data acquisition, to place several artificial targets (which are generally spheres or planar targets) in different points of the building which could be captured by the indoor and by the outdoor system. The minimum number of targets are 4 but it is recommended around 8-10 to have more accuracy in the results. These targets need to be placed at the entrance of the building, at different heights (on the façade if possible) and on the roof. In case of choosing this type of registration action the user just only requires identifying the targets in both point clouds and then register with the software.

In the following Table 17 a summary of all the methods is shown.

Table 17. Comparison between registration methods

Type of registration	Work in field	Work in office	Possible limitations
Direct geo-referencing (Only GPS points)	Requires that both 3D point clouds have georeferencing data	There is not needed (at least in most of the cases)	GPS signal
Registration by means of overlap areas	it is required a common area between datasets (around 20-30% of the total)	Registration using the software	Not enough overlap data
Registration by means of artificial targets	It is required at least to place 4 common artificial targets between point clouds	Registration using the software	Could be difficult to recognize targets due to the density of the data.

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