BUILDSPACE

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

D3.3 BUILDSPACE core platform and services (final)

June 2025

Document history

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Abbreviations and acronyms

Acronym	Description
API	Application Programming Interface
AR	Augmented Reality
BGI	Blue-Green Infrastructure
BIM	Building Information Model
CI/CD	Continuous Integration and Continuous Delivery/Deployment
CDD	Cooling Degree Days
CMIP6	Coupled Model Intercomparison Project Phase 6
CWS	Copernicus Web Services
DEM	Digital Elevation Model
DHW	Domestic Hot Water
DT	Digital Twin
DSM	Digital Surface Model
DTM	Digital Terrain Model
EDC	Eclipse Dataspace Connector
EGNSS	European Global Navigation Satellite System
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EO	Earth Observation
gDT	geometric Digital Twin
GIS	Geographical Information System
HAS	High Accuracy Service (from Galileo)
HDD	Heating Degree Days
IaaS	Infrastructure-as-a-Service
IaC	Infrastructure as Code

Acronym	Description
IDS	International Data Spaces
IDSA	International Data Spaces Association
IFC	International Foundation Class
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
ML	Machine Learning
NDVI	Normalised Difference Vegetation Index
OSM	OpenStreetMap
PaaS	Platform-as-a-Service
PCA	Principal Component Analysis
PCD	Point Cloud Data
PCL	Point Cloud Library
PV	Photovoltaic
RCP	Representative Concentration Pathway
RGB	Red, Green, Blue
SE	Service
SECAP	Sustainable Energy and Climate Action Plan
SLAM	Simultaneous Localisation And Mapping
SSP	Shared Socioeconomic Pathway
TMY	Typical Meteorological Year
UAC	Urban Atlas Cover
UAV	Unmanned Aerial Vehicle
UCZ	Urban Climate Zones
UHE	Urban Heat Exposure
UHR	Urban Heat Risk

Acronym	Description
UHV	Urban Heat Vulnerability
UI	User Interface
VR	Virtual Reality
WP	Work Package
YOLO	You Only Look Once
FAIR	Findable, Accessible, Interoperable, and Reusable

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Executive summary

This deliverable (D3.3) presents the final release of the BUILDSPACE core platform and services, concluding the work carried out under WP3: "**BUILDSPACE location-based and remote sensing applications development**." It builds upon the previous two releases (D3.1 and D3.2), integrating final developments, pilot customisations, validations, and overall conclusions. The platform and services are now fully developed, tested, and aligned with the objectives of the project and the broader goals of the European Green Deal.

The **BUILDSPACE Core Platform** has matured into a robust, modular digital infrastructure that supports the integration, processing, and visualisation of diverse data sources, including Copernicus satellite services, EGNSS (Galileo HAS), IoT sensors, UAV-acquired imagery, BIM models, and climate projections. It enables seamless user access to geospatial datasets, service-specific results, and co-created decision-support tools through a unified interface and an API-supported backend.

The five services developed under WP3 include:

- **SE1 – Digital Twin Generation**: Automatic generation and visualisation of 3D geometric digital twins, integrated with high-precision GNSS data.
- **SE2 – Digital Twin Enrichment**: UAV- and SLAM-based building envelope inspection using RGB and thermal imagery to identify anomalies such as cracks, dampness, and solar panel failures.
- **SE3 – Built Environment Climate Scenarios**: Energy demand estimation under current and future climate conditions, incorporating retrofitting strategies and solar photovoltaic (PV) potential.
- **SE4 – Urban Heat Analysis and Resilience**: Assessment of urban heat exposure and vulnerability, supporting adaptation planning based on spatial and demographic indicators.
- **SE5 – Urban Flood Analysis and Resilience**: Evaluation of flood risks and adaptation potential, integrating land use data, rainfall projections, and blue-green infrastructure analysis.

The services have been tailored and validated across four European pilot sites, demonstrating adaptability to different data contexts, climatic conditions, and user needs. Throughout the development, strong synergies between services were fostered, reinforcing the coherence and replicability of the platform.

This deliverable also reflects on the lessons learned during the development and integration process, highlighting the value of modular design, user co-creation, and the strategic use of Earth Observation data. WP3 has delivered a mature, interoperable suite of services ready to support sustainable urban planning and climate resilience across Europe.

1. Introduction

The BUILDSPACE project, funded under Horizon Europe, aims to harness the potential of satellite data, digital twins and emerging technologies to improve **energy efficiency in buildings** and enhance **climate resilience in cities**. It develops an integrated platform and five decision support services to assist stakeholders -ranging from local authorities to construction professionals and citizens- in making informed decisions for sustainable urban planning.

This Deliverable 3.3 reports on the **third and final technology release** of the BUILDSPACE core platform and services, representing the culmination of the development efforts within **Work Package 3 (WP3): BUILDSPACE location-based and remote sensing applications development**. WP3 has played a central role in implementing the project's digital infrastructure and services, building on user needs and technical requirements defined in WP2, and contributing directly on the integration and testing activities led by WP4.

The BUILDSPACE core platform integrates data from IoT devices, UAVs, BIM models and satellite services such as **Copernicus and EGNSS Galileo**, offering a robust backend and user-friendly frontend for the deployment, access and management of BUILDSPACE services.

The five services developed in WP3 are structured across two levels of application: building scale and city scale, as shown in Figure 1.

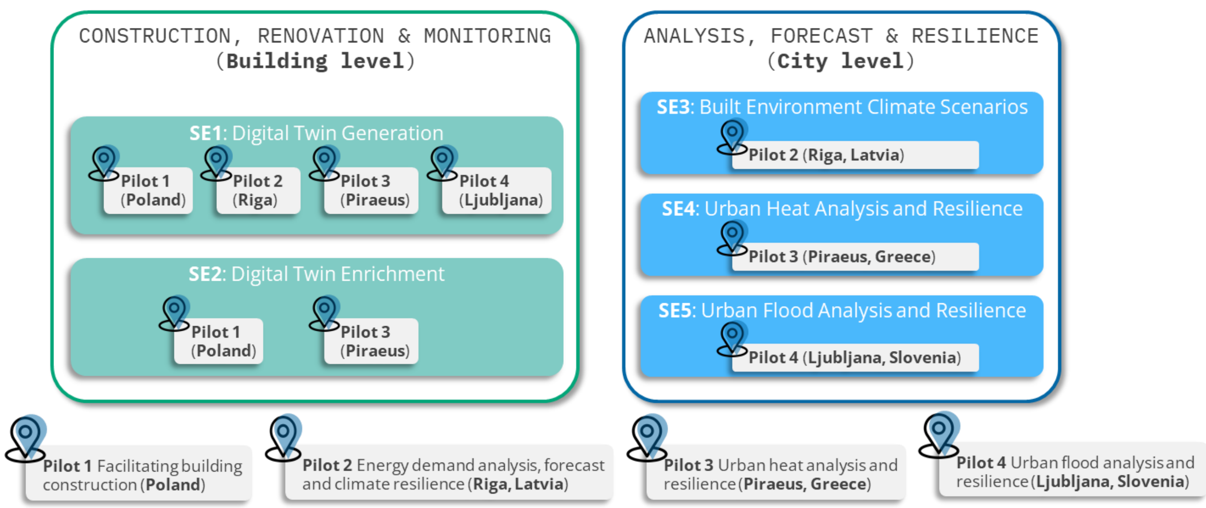

Figure 1. Overview of BUILDSPACE services and their connection with the four pilot sites

These services have been configured and deployed in four EU pilot sites, tailored to local conditions and datasets, and are supported by a modular, scalable platform architecture.

Deliverable 3.3 captures the final development cycle (M29: June 2025), completing the iterative methodology designed for BUILDSPACE, which includes three progressive stages of release and validation. The overall process is summarised in Figure 2.

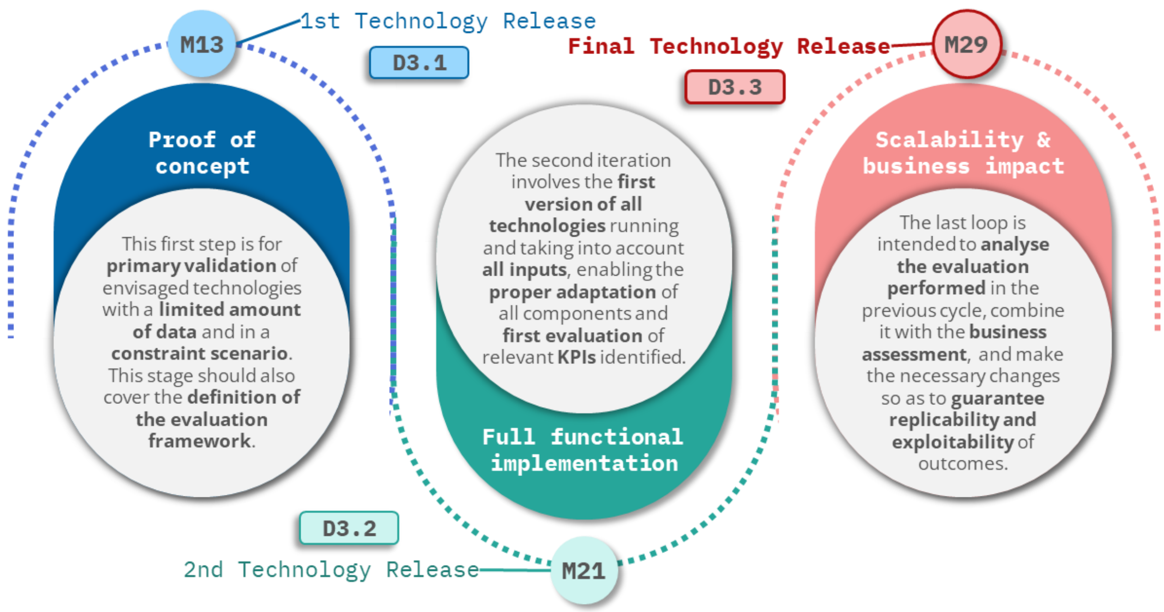

Figure 2. Iterative development methodology and corresponding deliverables for BUILDSPACE technology releases

Each iteration has incorporated feedback from stakeholders, input from co-creation activities and progressive integration of key technologies to enhance maturity, usability and performance.

Within each iteration, WP3 followed a consistent development workflow for the services and platform components, structured as shown in Figure 3.

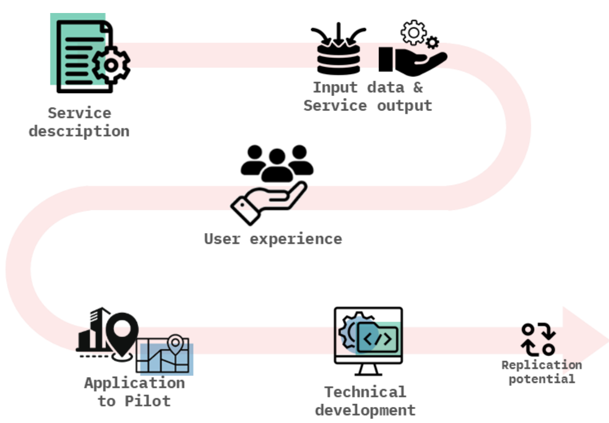

Figure 3. WP3 methodological workflow for the definition and development of platform and services

This workflow ensured alignment with **WP2**, which provided a structured approach to user story development, requirement elicitation and co-creation with stakeholders. WP2's outcomes directly informed the functional specifications and interface design of the services.

At the same time, **WP4** plays a key role in validating the services in real-life conditions across pilot sites, as well as in evaluating their **replicability and scalability** for future adoption. This tight collaboration between WP2, WP3 and WP4 ensures that BUILDSPACE outputs are **demand-driven**, technically sound and aligned with real urban and building-scale challenges.

1.1.Deliverable structure

The present Deliverable 3.3 constitutes the third and final report under WP3. It documents the full development of the BUILDSPACE core platform and the five decision-support services, consolidating the progress made in the previous two releases (D3.1 and D3.2) and presenting the final integrated version of all components.

The document is **structured** in the following sections:

- **Section 1**, the current section, **introduces** the context and objectives of the deliverable within WP3.
- **Section 2** focuses on the BUILDSPACE **Core Platform**, providing a description of the consolidated architecture, the updates at the interoperability layer, and the lessons learned.
- **Sections 3 to 7** are devoted to the **five BUILDSPACE services**, highlighting the scale of application (building or city):
    - **Section 3** presents the ***Digital Twin Generation*** (**SE1**) service at building scale.
    - **Section 4** covers the ***Digital Twin Enrichment*** (**SE2**) service at building scale.
    - **Section 5** describes the ***Built Environment Climate Scenarios*** (**SE3**) service at city scale.
    - **Section 6** addresses the ***Urban Heat Analysis and Resilience*** (**SE4**) service at city scale.
    - **Section 7** presents the ***Urban Flood Analysis and Resilience*** (**SE5**) service at city scale.

  Each of these service sections follows a common structure to ensure clarity and coherence across the document:
    - **Sub-section X.1** describes the **inputs** required and **outputs** produced by the service.
    - **Sub-section X.2** outlines the **user experience**, detailing the interface, user navigation flows, visualisation modes and key functionalities. It also briefly describes the target users and added value of the service, and includes technical feedback from user experience observations where relevant.
    - **Sub-section X.3** explains how the service was **adapted to** meet the specific neds and requirements of each **pilot**.
    - **Sub-section X.4** presents the **final technical developments**, including system architecture, software components, algorithms, and the main improvements since the second release.
    - **Sub-section X.5** explores the service’s **potential for replication and uptake**, including considerations such as modularity, scalability, and lessons learned. It also presents qualitative insights from preliminary validation.
- **Section 8** provides a transversal reflection on the development of the platform and services, outlining key **lessons learned, technical challenges encountered and recommendations** for future exploitation, scalability and integration across services.
- **Section 9** **concludes** the document with a summary of key achievements and final remarks regarding WP3’s contribution to the overall BUILDSPACE objectives.

2. BUILDSPACE Core Platform – Final version

This final iteration of the BUILDSPACE Core Platform consolidates the developments and integrations made throughout the project into a robust, nearly production-ready system. The platform enables data acquisition, management, and federated sharing for urban applications, both within the BUILDSPACE trusted ecosystem and with external services. Below is an overview of the consolidated architecture (Figure 4), available services, user interface, technical validations, and improvements over the previous iteration (as described in D3.2).

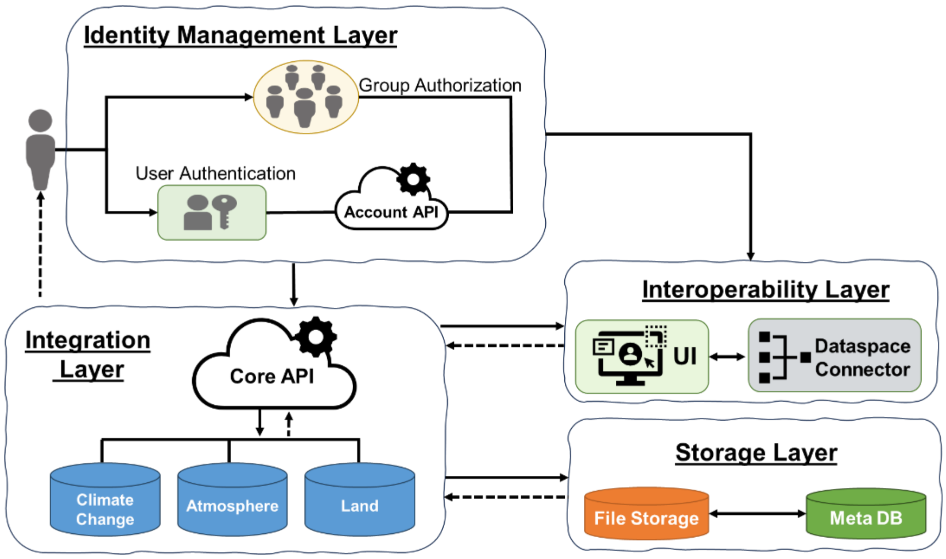

Figure 4. BUILDSPACE Core Platform final architecture

2.1. Consolidated architecture

The final architecture of the BUILDSPACE Core Platform has been organized into well-defined layers, each responsible for a specific set of functionalities. These layers together form a scalable, secure, and interoperable system that supports urban and climate data workflows, while enabling federated data sharing both within the BUILDSPACE ecosystem and with external digital ecosystems via IDS-compliant mechanisms. Below is a detailed overview of each layer, as implemented and validated in the final development phase.

Identity management is the top-level layer that provides all the necessary mechanisms for user access, interaction, and role management. It is composed of an integrated Keycloak instance, combined with a REST API (Accounts API), enabling secure user authentication and organizational authorization. This layer governs both authentication (who a user is) and authorization (what a user is allowed to access), establishing the foundations for the security of the platform operations. In more detail, identity is handled at the user level, where each individual has a unique account authenticated via Keycloak. However, access to data and platform functionality is granted on an organizational level, meaning users operate on behalf of one or more organizations to which they are affiliated. This design choice supports inter-organizational collaboration by allowing datasets and resources to be managed within the context of organizational entities rather than individuals. It enables clear governance over data ownership, sharing, and control, and ensures that only authorized personnel within an organization can access or manage specific datasets or services.

The **integration layer** is responsible not only for distributing data within the BUILDSPACE ecosystem but connecting external data sources with the Core Platform's backend as well. It provides interfaces to Copernicus services (Climate Change, Atmosphere, and Land), enabling users to search, request, and retrieve datasets through a unified API. A fingerprinting mechanism ensures deduplication of requests and efficient dataset reuse. This layer also includes a GNSS module that integrates the Galileo High Accuracy Service (HAS) via an NTRIP caster hosted at https://galileo-buildspace.euinno.eu[1], offering real-time high-precision positioning data. All services within this layer are exposed through RESTful APIs documented with Swagger, supporting both frontend and programmatic access.

Storage is handled in the respective **storage layer**. File storage is provided by MinIO, an on-premises, S3-compatible object store that ensures fast, scalable, and secure handling of data resources, in the form of Binary Language Objects (BLOBs), thus promoting type agnosticism and supporting any file format. Metadata is stored in a dedicated non-relational database, namely MongoDB. This choice enables the platform to support flexible and extensible metadata structures, tailored to the diverse needs of urban and climate-related datasets. Overall, this dual-storage setup enables the platform to effectively manage large volumes data while providing rich metadata.

The **interoperability layer** serves as the main interface of the BUILDSPACE Core Platform, enabling both internal, trusted users and external stakeholders to interact with the platform's datasets and resources. It ensures that the platform operates not only as a standalone urban data platform, but also as a node within a wider data ecosystem, compliant both with FAIR and IDS principles. In more details, for trusted users within the BUILDSPACE ecosystem, interoperability is provided through a CKAN instance. CKAN has been extended to use the REST API of the Integration layer as the main backend point and acts as the platform's primary user interface, allowing authenticated users to discover, upload, manage, and share datasets within and across organizations. Its rich metadata capabilities, search interface, preview tools, and role-based access controls make it suitable for data providers, municipalities, and service operators. CKAN integrates tightly with the identity management layer, ensuring that all interactions reflect the permissions and organizational structures enforced by the platform.

For external users and systems operating outside the BUILDSPACE ecosystem, the platform enables controlled, policy-based access via an Eclipse Dataspace Connector (EDC). The EDC is fully integrated into the backend and listens for the creation of new public datasets. When such a dataset is published through CKAN, the platform automatically extracts its metadata, license, and file access URL, and registers it as an asset in the EDC Connector. Each asset is exposed with a usage policy that aligns with its declared license, ensuring that data sharing is legal, traceable, and compliant with the IDS reference architecture (Figure 5). Only public datasets are eligible for publication; private and restricted datasets are excluded to

[1] The link provided is not accessible via a standard web browser. It is an NTRIP caster intended for use through applications supporting the NTRIP protocol, such as BKG Ntrip Client (BNC) (https://igs.bkg.bund.de/ntrip/bnc). More information is available in Deliverable 3.2.

preserve data sovereignty and compliance with governance rules. More details are provided in the next section.

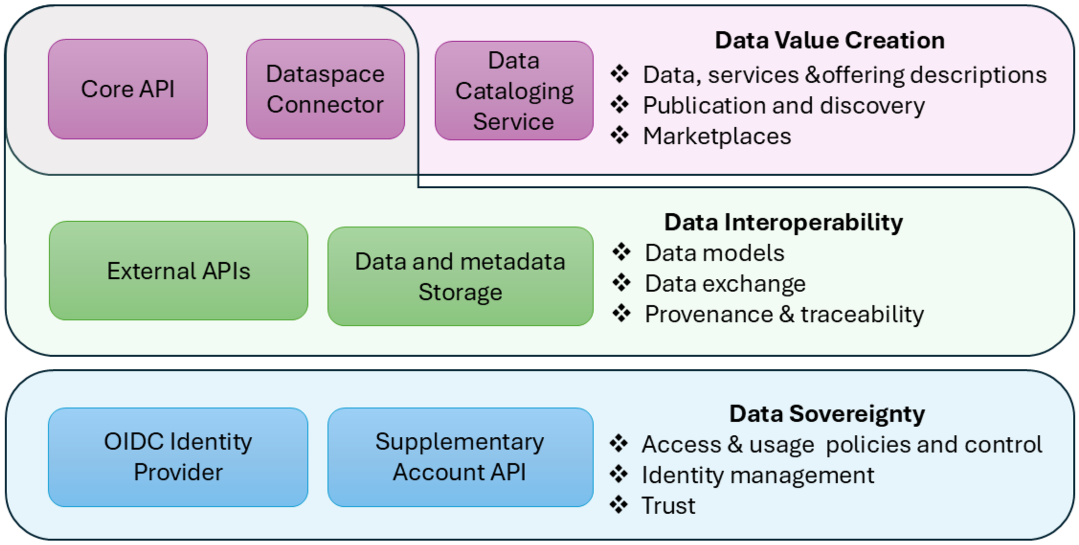

Figure 5. Core Platform's alignment with the Dataspaces initiative

The interoperability layer plays a critical role in fulfilling the BUILDSPACE vision of cross-organizational collaboration and open, federated data participation, enabling the platform to function both as an internal operational tool and as a trusted data provider in broader European or global data spaces.

2.2.Updates at the interoperability layer – dataspaces federation

In the initial iterations of the BUILDSPACE Core Platform, the Interoperability Layer was implemented solely through the CKAN frontend. This allowed authenticated users within the BUILDSPACE environment to discover, manage, and share datasets through an intuitive user interface, with access governed by role-based permissions and organizational affiliation. While CKAN remains a core component for internal interoperability, the platform has now been extended to support external data exchange through the integration of the IDS-certified Eclipse Dataspace Connector (EDC).

This significant architectural enhancement enables the platform to expose public datasets beyond its internal environment in a secure, policy-controlled, and IDS-aligned manner. The newly added EDC Connector operates alongside CKAN and serves as the gateway to the external stakeholders. It provides all necessary components for publishing datasets, defining usage policies, managing contract agreements, and executing secure data transfers with external IDS-compliant consumers. The integration is fully operational and visible through a dedicated BUILDSPACE Connector dashboard, accessible at https://connect-buildspace.euinno.eu/. From this interface (Figure 6), data providers can monitor incoming and outgoing transfer processes, manage assets and policies, create data offers, and establish contract agreements.

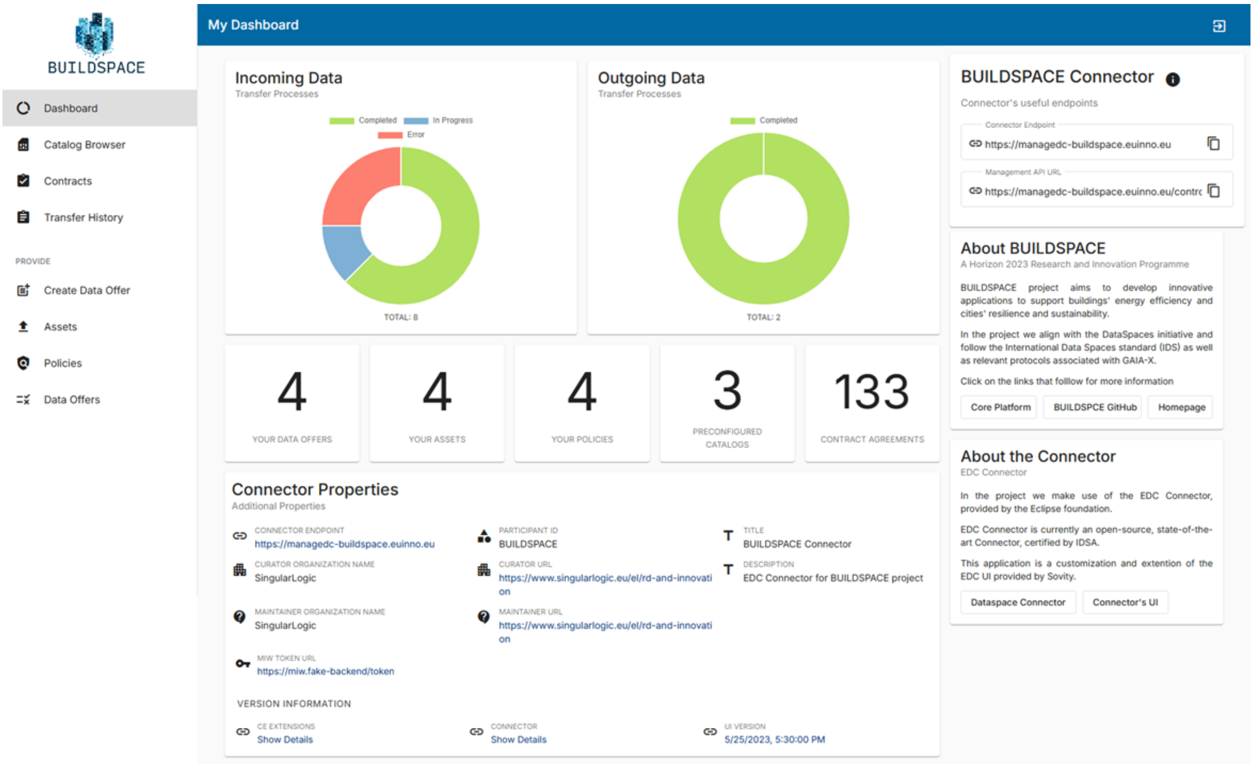

Figure 6. BUILDSPACE Connector's user interface

In more details, each user can log in to the connector's interface and is empowered to define access policies and create data offers. As shown in Figure 7, users can compose custom policy expressions using predefined constraints such as consumer participant ID, time restrictions, and timespan restrictions. These expressions allow data providers to control who can access a dataset, when it can be accessed, and under what conditions. The platform also supports logical composition of multiple conditions through the "Combine" option, enabling complex, multi-dimensional usage policies. Once a policy is defined, it can be attached to any asset, that the user is authorized to manage, and used to create a data offer. These data offers are discoverable by external IDS-compatible connectors and serve as the foundation for establishing contract agreements through the EDC.

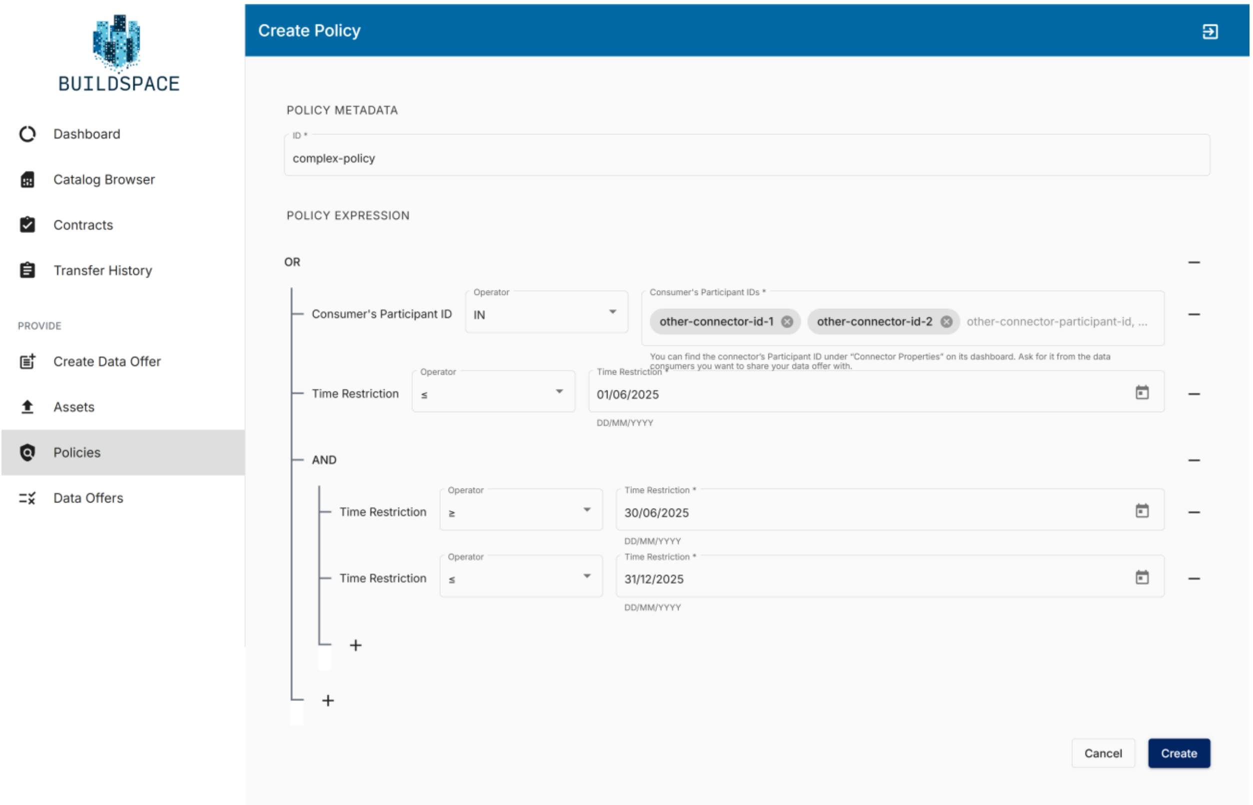

Figure 7. EDC policy creation

To ensure consistency with the BUILDSPACE authorization model, users may only manage assets that belong to organizations they are affiliated with. Although all users have visibility into the EDC Connector and its policy management capabilities, they are only permitted to create data offers for assets owned by their organization. This model reflects the organization-based access control enforced throughout the Core Platform, ensuring that asset governance, publishing rights, and data exposure responsibilities are preserved at the organizational level.

Through this mechanism, the BUILDSPACE platform offers a federated yet secure environment for controlled data exchange. Policies ensure that data is only accessed under well-defined conditions, while organizational constraints guarantee that data ownership is respected and externally shared datasets are curated by authorized representatives. This design significantly extends the platform's reach, since external services, outside the BUILDSPACE ecosystem, can use the data collected in the project in a secure manner, while promoting data sovereignty. CKAN remains the trusted frontend for internal users and organizational collaboration, while the EDC Connector enables federated, standards-based data sharing in line with the International Data Spaces (IDS) architecture and GAIA-X principles. This dual-mode interoperability model ensures that BUILDSPACE can serve both as a secure internal data hub and as an active participant in broader, cross-domain dataspaces.

2.3.Overview of Copernicus data integration across BUILDSPACE services

To ensure alignment with the objectives of the Horizon Europe programme and fully exploit the potential of Earth observation data, BUILDSPACE integrates Copernicus core services, particularly the **Climate Change Service (C3S)** and the **Land Monitoring Service (CLMS),** into the design and implementation of several of its decision-support services. The use of Copernicus datasets enhances the scientific robustness, interoperability, and European-scale replicability of the BUILDSPACE services, especially those operating at city level.

Table 1 below provides a comprehensive overview of the Copernicus services and data products utilised across the five BUILDSPACE services, outlining their specific role in each case.

Table 1. Use of Copernicus services and datasets in BUILDSPACE services

BUILDSPACE service	Copernicus core service	Dataset(s) used	Purpose
SE1: Digital Twin Generation	**CLMS**	• Digital Elevation Model (DEM)	Georeferencing and 2D/3D terrain context for gDT/PCD visualisation in GIS environments
SE2: Digital Twin Enrichment	**CLMS** (indirect)	• DEM, CORINE Land Cover (optional)	Contextual environmental information to enrich visualisation of UAV/SLAM models
SE3: Built Environment Climate Scenarios	**C3S**	• CMIP6 Scenarios (SSPs-RCPs), • ERA5 hourly data	Energy demand forecasting under future climate conditions (CMIP6 scenarios)
SE4: Urban Heat Analysis and Resilience	**CLMS & C3S**	• CORINE Land Cover, • NDVI, • DEM, • ERA5	Urban heat distribution and intensity modelling, vulnerability analysis
SE5: Urban Flood Analysis and Resilience	**CLMS & C3S**	• Urban Atlas, • CORDEX indices (e.g. Rx1day)	Flood hazard (damage) mapping, runoff modelling, blue-green infrastructure impact

2.4.Cloud computing infrastructure

The BUILDSPACE cloud infrastructure aims at ensuring the scalable and modular deployment of the project's services by leveraging modern cloud-native technologies. Built upon Infrastructure as Code (IaC) principles and DevOps practices, it promotes reproducibility, automation and observability across distributed environments. It is designed to meet the project's data processing needs by enabling seamless orchestration of containerized services, secure storage and monitoring. The following paragraphs present the key components and configuration strategies used to manage and orchestrate BUILDSPACE services, covering Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), GitOps workflows and tools supporting Infrastructure as Code (IaC).

2.4.1.Infrastructure-as-a-Service (IaaS) and Platform-as-a-Service (PaaS)

BUILDSPACE leverages the ECMWF Common Cloud Infrastructure, which is in turn part of the European Weather Cloud, jointly managed by ECMWF and EUMETSAT. It is powered by OpenStack[2], an open-source cloud computing platform, as the IaaS layer. OpenStack provides an abstraction over physical resources, allowing the provisioning of virtual machines, the configuration of virtual networks and the management of persistent storage in a flexible and scalable way. This foundational layer ensures dynamic resource allocation, quotas enforcing and tenant isolation.

The PaaS layer is constructed atop OpenStack and is based on a containerised architecture managed by Kubernetes[3], with Rancher Cluster Manager[4] as the orchestration and management solution.

2.4.2.GitOps tools

To support the DevOps and GitOps practices, GitLab[5], a collaboration oriented open-source web-based tool, has been deployed for the project. GitLab provides capabilities for:

- the hosting of Git repositories (including both application source code and infrastructure or platform-level configuration files);
- continuous integration and continuous delivery (CI/CD) pipelines definition, for building and deploying containerised applications, as well as managing infrastructure resources;
- a container images registry, which can be leveraged by Kubernetes.

Along with GitLab, the Hashicorp Vault[6] service has been deployed, for the management of application and infrastructure secrets. Vault provides different types of API and allows for the definition of fine-grained access policies.

2.4.3.Infrastructure as Code (IaC)

IaC is a central principle of the BUILDSPACE cloud infrastructure, allowing for the declarative and automated provisioning of computing environments. The implementation combines Terraform[7] and Ansible[8], orchestrated through version-controlled workflows in GitLab, as shown in Figure 8. Terraform enables the definition and management of cloud infrastructure through configuration files, supporting the provisioning of virtual machines, networks, and Kubernetes clusters within OpenStack. These configurations are structured into reusable modules, which encapsulate specific logic and allow consistent, portable deployment patterns. Complementing this, Ansible automates post-provisioning tasks such as software installation, system configuration, and service orchestration. Ansible playbooks are integrated into the deployment pipeline to apply consistent configurations across environments.

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[2] Open Infrastructure Foundation, OpenStack, https://www.openstack.org
[3] Cloud Native Computing Foundation, Kubernetes, https://kubernetes.io
[4] SUSE, Rancher Kubernetes Management Platform, https://www.rancher.com
[5] GitLab Inc., GitLab: The DevSecOps Platform, https://about.gitlab.com
[6] HashiCorp, Vault by HashiCorp, https://www.vaultproject.io
[7] HashiCorp, Terraform by HashiCorp, https://www.terraform.io
[8] Red Hat, Ansible Automation Platform, https://www.ansible.com

GitLab plays a pivotal role in managing this IaC workflow. CI/CD pipelines hosted in GitLab automatically trigger infrastructure builds, updates, and validations when new commits are pushed to the repository. This ensures that deployments are reproducible, auditable, and aligned with DevOps best practices. By integrating infrastructure management into the software development lifecycle, this approach improves deployment speed, consistency, and disaster recovery. It enables teams to trace infrastructure changes over time and promotes collaborative development by using familiar version control and review mechanisms.

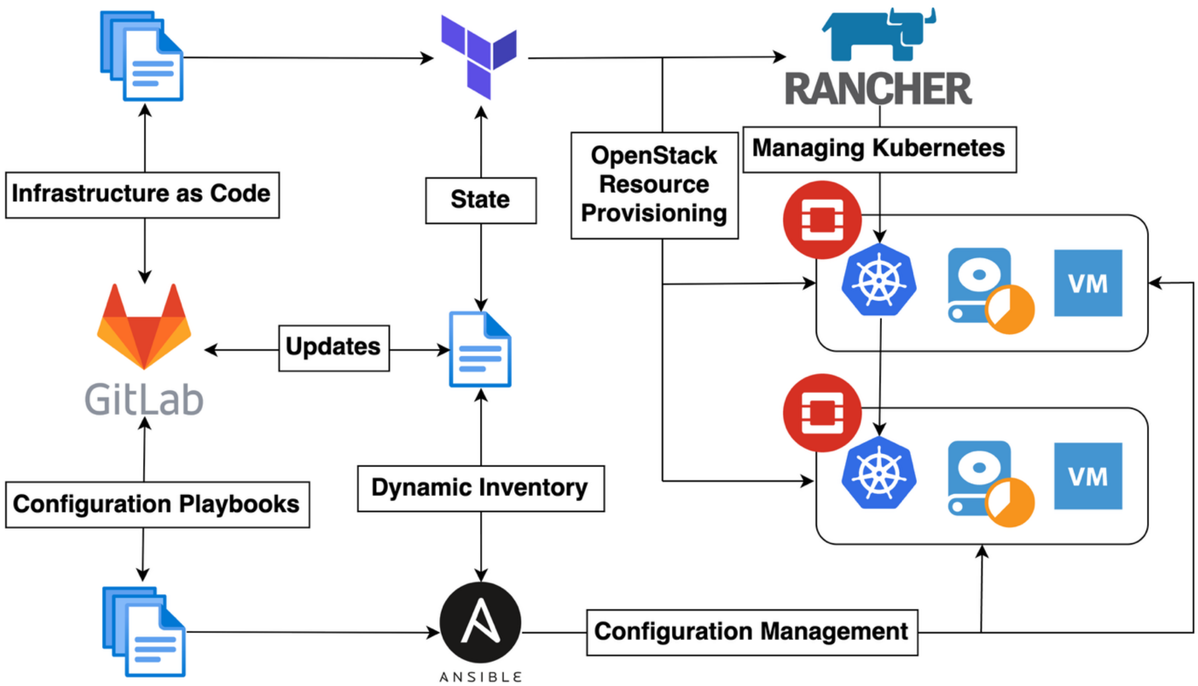


Figure 8. BUILDSPACE Infrastructure as Code architecture

2.5. Lessons learned

The Core Platform functions as the backbone of the BUILDSPACE project, supporting all services by enabling both centralized identity management and data storage, sharing, and visualization in a unified and secure environment. Designed to serve as a common layer across the entire ecosystem, the platform facilitates interoperability between heterogeneous data sources and services by exposing standardized APIs and harmonized metadata models.

The Core Platform acts as the gateway to the BUILDSPACE services, leveraging CKAN for dataset management, Keycloak for identity and access control, and a set of APIs that make data retrieval and interaction seamless across domains. All datasets were registered under structured organizations. These datasets were published following a consistent schema and were accessible either through the CKAN web interface or directly via the CKAN API, enabling integration with the services.

Crucially, the Core Platform also integrates a fully functional IDS Dataspace Connector, aligned with the International Data Spaces Association (IDSA) reference architecture. This connector allowed BUILDSPACE to publish selected datasets to trusted external parties or other domains, supporting contract negotiation, and policy enforcement. Through the Dataspace Connector, organizations participating in BUILDSPACE retained full data sovereignty while still enabling interoperable data sharing within and beyond the project scope.

Several BUILDSPACE services leveraged the Core Platform directly. For example, the Digital Twin Enrichment service (SE2) published RGB and thermal point clouds enriched with semantic and structural metadata. In addition, to support the Urban Heat Analysis and Resilience service (SE4), weather data were stored in the platform.

3. BUILDSPACE service SE1 – Digital Twin Generation (building scale)

The SE1 – Digital Twin Generation focuses on four main components:

1. The generation of a digital twin (DT) model in IFC format from point cloud data (PCD).
2. The updating of this model to reflect construction progress using multiple drone-based point clouds.
3. The integration of GIS data into the generated or updated DT.
4. The visualisation of the results.

This comprehensive solution is applied across the four pilot sites, involving five buildings in real-world scenarios.

For the **DT generation**, a custom training dataset was created based on data from Pilot 2 (Riga). Point cloud segmentation is performed using the PointNet++ machine learning algorithm. Subsequently, geometric information is extracted using a self-developed algorithm, which is then converted into an IFC-format digital twin using another custom-developed converter.

The **DT updating** process also relies entirely on in-house algorithms. These updates include the alignment of all drone-based PCDs with the original BIM model, analysis of point proximity metrics for object-level progress monitoring, and the enrichment of IFC files with customized construction status attributes. Augmented reality (AR) visualizations were tested on-site using Trimble software as part of this update functionality.

For the **GIS data integration**, the generated or updated DT models are geolocated using real-world coordinates. These models are then integrated with GIS maps to allow combined visualization in a geospatial context.

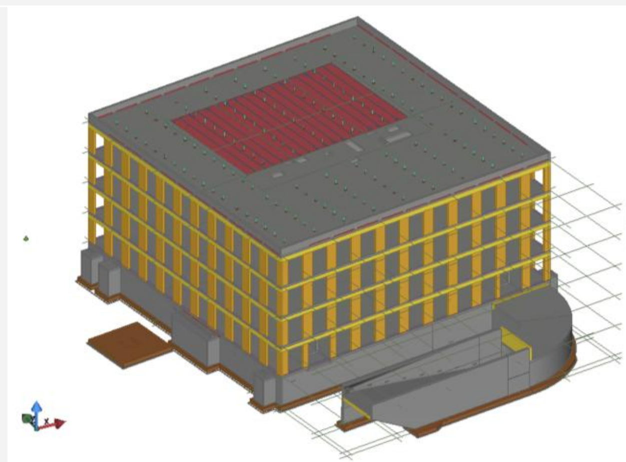
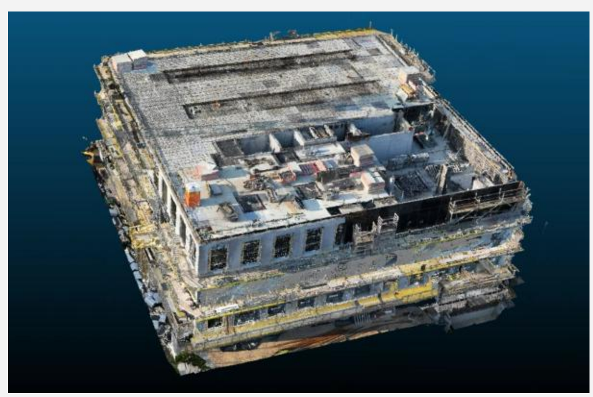
The **visualisation component** supports three modes: (i) screen-based visualization, applied in Pilots 2, 3, and 4; (ii) virtual reality (VR), implemented for the Rectorate of Poznan University of Technology (Pilot 1); and (iii) augmented reality, used for The Faculty of Psychology at the University of Warsaw (also in Pilot 1). The screen-based visualization will be directly integrated into the BUILDSPACE Core Platform, while the VR version will be provided as a downloadable package. Due to specific software requirements, the AR output will be delivered directly to the pilot team for on-site testing, although it can also be accessed using the same interface as the screen-mode version.

In summary, SE1 combines multiple point cloud sources, including terrestrial and airborne laser scanning as well as drone imagery, to generate and manage digital twin models for diverse building types. The complexity of the task, driven by the heterogeneity of data sources and the number of variables, underlines the technical sophistication of this service.

3.1.1.Input

As described above, the input of the five buildings in four pilot projects are mainly the PCD data and IFC data. The geolocation information of the five buildings is also provided by the pilot teams. The following Table 2 and Table 3 include the input data of SE1.

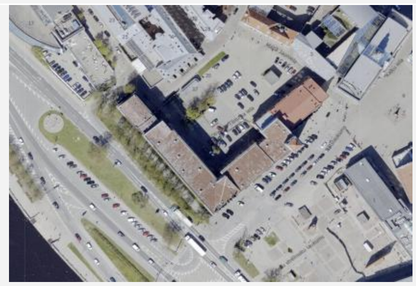
Table 2. Input data of SE1

Pilot	Raw data source	Data input	Reference
Pilot 1 – Rectorate of Poznan University of Technology	Drone images	PCD	 **Figure 9. PCD data of Pilot 1, UC1.1**
Pilot 1 – The Faculty of Psychology of the University of Warsaw	As-designed BIM data (.ifc format) and drone	As-designed BIM data (.ifc format) and multiple PCDs generated from drone images	 **Figure 10. As-designed BIM model (.ifc) with scheduled construction progress information.**  **Figure 11. Exampled PCDs generated through photogrammetry, there are 10 PCDs in this scenario (UC1.2).**

Pilot	Raw data source	Data input	Reference
Pilot 2 – Kaļķu iela 1, Riga, Latvia	Terrestrial laser scanner and airborne laser scanner	PCD	 **Figure 12. Scanned building of Pilot 2**
Pilot 3 – The 21st Elementary School building of Piraeus	Drone images	PCD	 **Figure 13. PCD constructed from drone images of Pilot 3**
Pilot 4 – The FKKT-FRI building of University of Ljubljana	Drone images	PCD	 **Figure 14. PCD constructed from drone images of Pilot 4**

Table 3. Input EGNSS data (geolocation) of SE1

Pilot	Building coordinates (WGS 84)	Reference
Pilot 1 – Rectorate of Poznan University of Technology	52.4049°N, 16.9502°E	

Pilot	Building coordinates (WGS 84)	Reference
Pilot 1 – The Faculty of Psychology of the University of Warsaw	52.2525° N, 20.9908° E	
Pilot 2 – Kaļķu iela 1, Riga, Latvia	56.9474° N, 24.1048° E	
Pilot 3 – The 21st Elementary School building of Piraeus	37.9418° N, 23.6515° E	
Pilot 4 – The FKKT-FRI building of University of Ljubljana	46.0506° N, 14.4677° E	

3.1.1.Output

The output of SE1 is the newly generated DTs and updated DT data. All the output data is consolidated into one platform with the accurate geolocation information. Figure 15 provides the geolocation of the four pilot sites (five buildings).

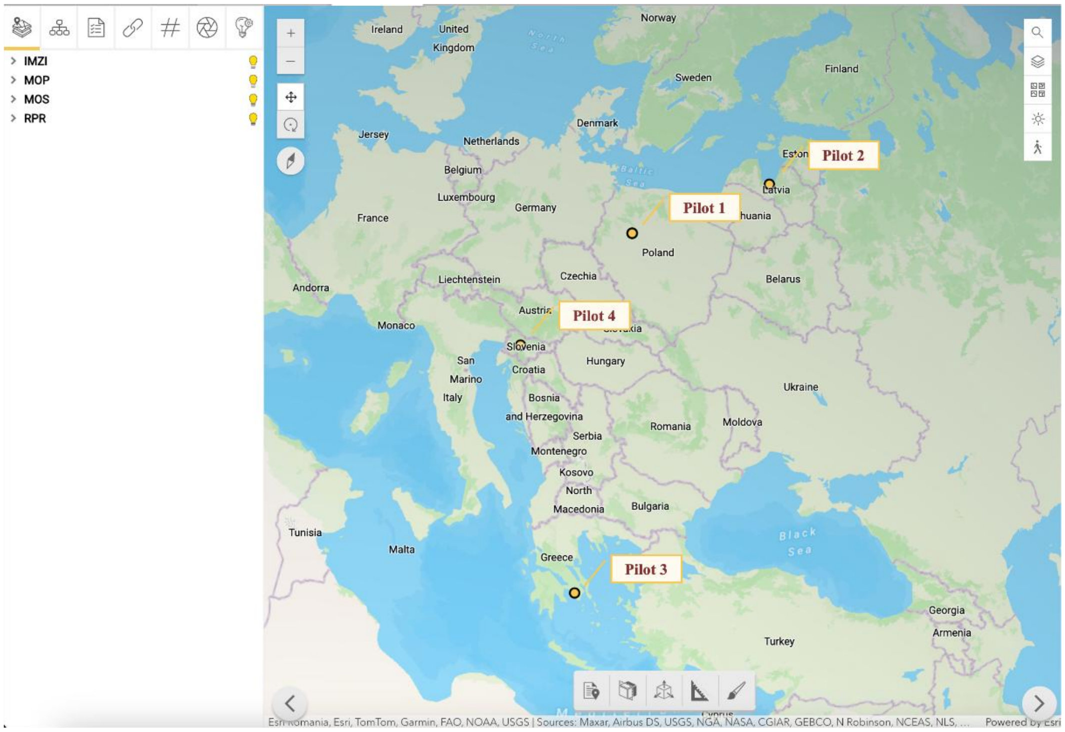
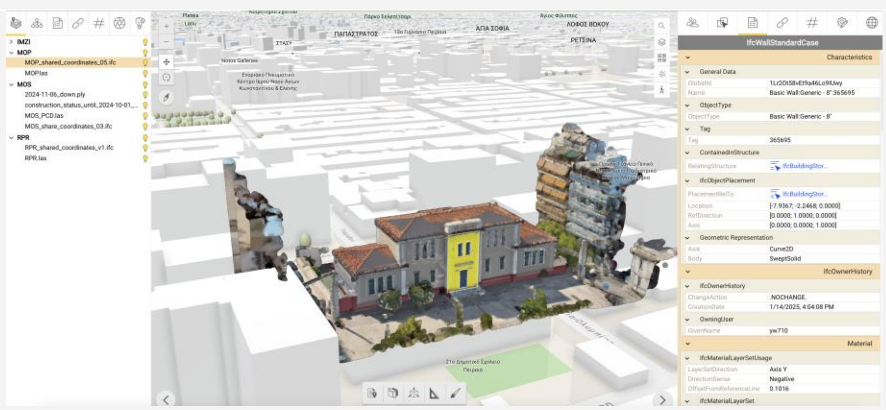


Figure 15. Visualisation of the geolocation of the four pilot sites

When zooming in the above Figure 15 into different pilot projects, the output of each pilot can be visualized, as in Table 4 below.

Table 4. Visualisation of output data

Pilot	Reference
Pilot 1 – Rectorate of Poznań University of Technology	 **Figure 16. Visualisation of integrated IFC and PCD data (Poznań – UC1.1)**

Pilot	Reference
Pilot 1 – The Faculty of Psychology of the University of Warsaw	 **Figure 17. Visualisation of integrated IFC and PCD data with the updated construction process information (Warsaw – UC1.2)**
Pilot 2 – Kaļķu iela 1, Riga, Latvia	 **Figure 18. Visualisation of integrated IFC and PCD data (Riga)**
Pilot 3 – The 21st Elementary School building of Piraeus	 **Figure 19. Visualisation of integrated IFC and PCD data (Piraeus)**

Pilot	Reference
Pilot 4 – The FKKT-FRI building of University of Ljubljana	 **Figure 20. Visualisation of integrated IFC and PCD data (Ljubljana)**

3.2.User experience

The user experience is covered by three sections: DT generation, DT updates and visualisation interface. The geolocation information integration and the visualization solution are also included in both sections 3.2.1 and 3.2.1. The automation levels of each step in the service are explained.

3.2.1.DT generation including GIS data integration and visualization

The automation conversion from PCD to DT is a complex process using the ML algorithm. It highly depends on the quality and source of raw data, relevance level between training dataset and target data.

Figure 21 and its corresponding table outline the step-by-step workflow of SE1, detailing the level of automation and clarifying the manual interventions required throughout the process. From the user's perspective, this service provides the automatic conversion from the PCD to IFC based on the provided algorithm, including semantic segmentation, mesh conversion, geometric information extraction, and final visualization.

However, as shown in the Table 5, certain stages still require manual input, particularly in cleaning raw data, preparing ML training sets, and adjusting DT model outputs. These manual tasks are critical to ensure the adaptability and robustness of the service when dealing with varied building types (e.g., residential, commercial, heritage) and diverse data sources, including terrestrial laser scans, airborne LiDAR, and drone imagery. While the service is designed to achieve a high degree of automation overall, the inclusion of domain-specific manual work enhances accuracy and generalizability, particularly in complex or irregular indoor environments.

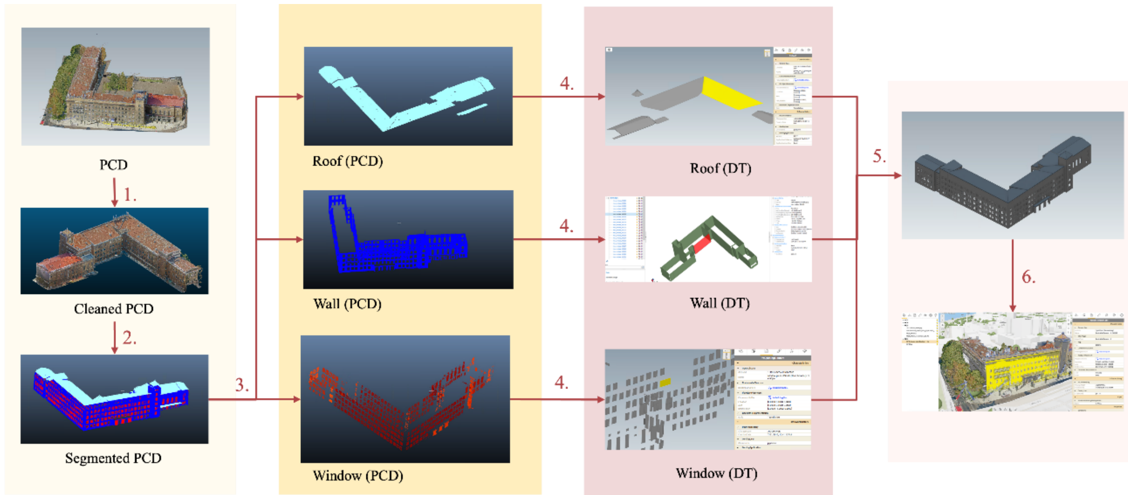


Figure 21. DT generation workflow

Table 5. Automation level for DT Generation

Step	Processing	Automation level	Notes – manual work clarification
1	Remove irrelevant parts of the point cloud; retain primary building elements including walls, roofs, and openings	Manual	Manual cleaning is required to filter out irrelevant data and preserve only structural elements.
2	PCD semantic segmentation using PointNet++	Partially automatic	The training dataset for the ML algorithm must be manually prepared. Segmentation is performed automatically by the PointNet++ algorithm, which is selected for its high performance. However, manual post-processing is needed to correct misclassifications.
3	Extract the segmented PCD, convert the PCD to mesh for geometric information retrieval	Fully automatic	-
4	Extract the geometric information and converting to DT format	Fully automatic	-
5	Manually adjust the imperfect DT elements, merge them to an integrated DT file and integrate the EGNSS geolocation information	Partially automatic	The manual work including the adjustment of the generated .ifc files (such as the gaps between the roof and wall). Based on the EGNSS geolocation information provided by the pilot teams, the EGNSS coordination is automatically enriched in the integrated DT (.ifc) file.
6	Visualization of the final generated DT	Fully automatic	-

3.2.1.DT updates including GIS data integration and visualization

Figure 22 and the corresponding Table 6 present the processing steps of DT updates with construction monitoring data. From the user's perspective, the entire workflow is fully automated, requiring no manual input at any stage. The process begins with automatic extraction of geometric and schedule-related information from the IFC file, followed by automatic mapping of these elements to the scanned PCDs. Undetected elements, which do not meet a predefined threshold of point density, are identified algorithmically and visually highlighted in red to indicate their incomplete or missing status. These results can be visualised in both AR-based and screen-mode interfaces. The EGNSS geolocation can also be integrated to the screen-mode platform as shown in Figure 21. Comparing to the DT generation process, this service relies on structured input and standardized comparison logic, eliminating the need for adaptation to different building types or scan sources.

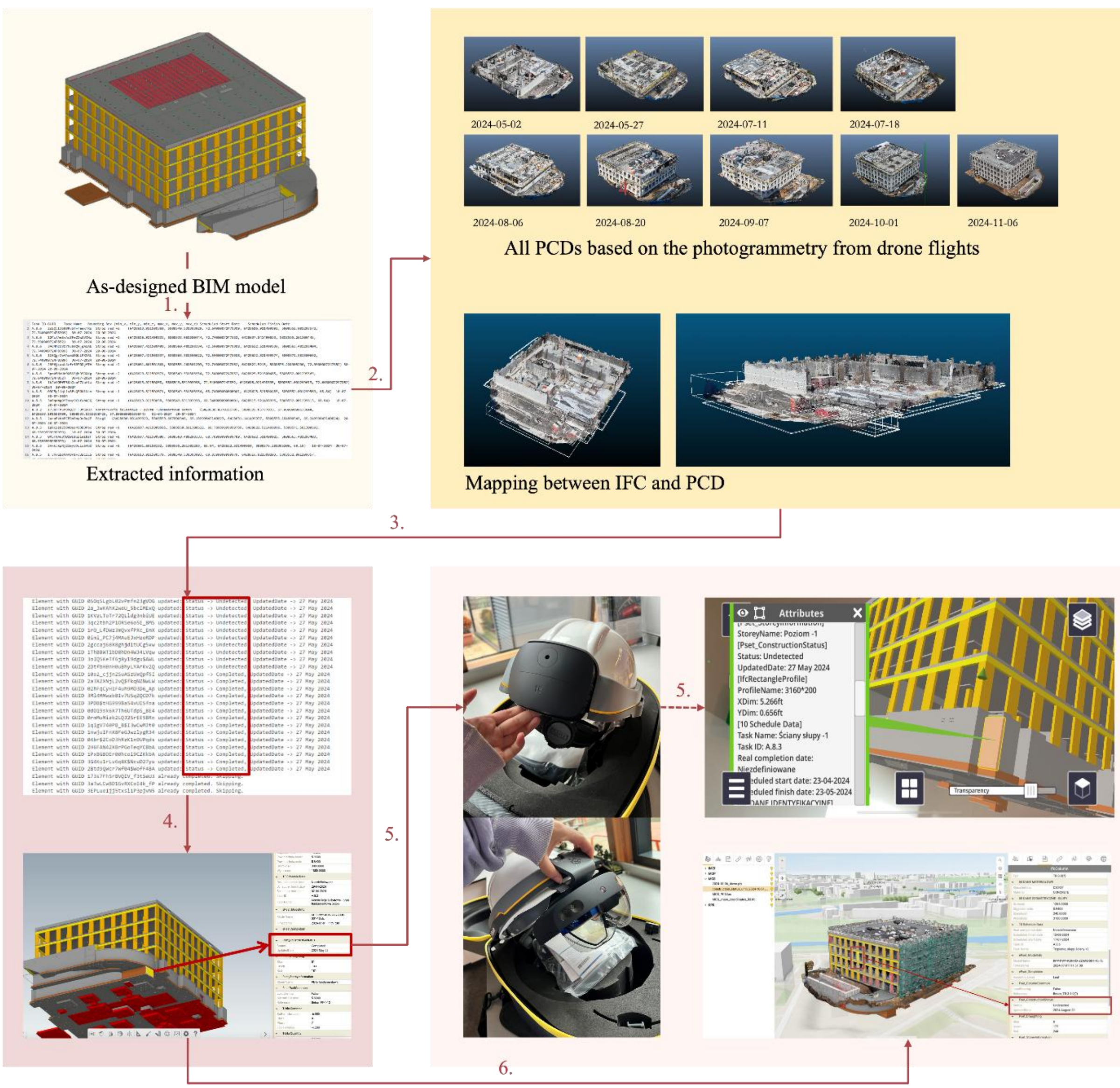


Figure 22. DT updates workflow

Table 6. Automation level for DT Generation

Step	Processing	Automation level
1	Extract information from ifc file, which is the as-designed BIM model with construction schedule information	Fully automatic
2	Map the extracted information to PCDs of all the scans	Fully automatic
3	Extract the undetected elements based on the no. of points of each IFC elements	Fully automatic
4	Highlight the ‘undetected’ elements to red	Fully automatic
5	AR-based visualization	Fully automatic
6	Screen-mode visualisation	Fully automatic

3.2.1.Visualisation interface

The landing page for SE1 and SE2 is integrated into a single interface, linked to the BUILDSPACE Core Platform (see Figure 23). For this deliverable, however, the visualisation interfaces are presented separately for SE1 and SE2. The visualization for SE1 focuses on the representation of the DT (including DT generation and updates), including geolocation details and the integrated display of PCD with DT elements. While the visualization for SE2 emphasizes the PCD display enriched with thermal imaging information.

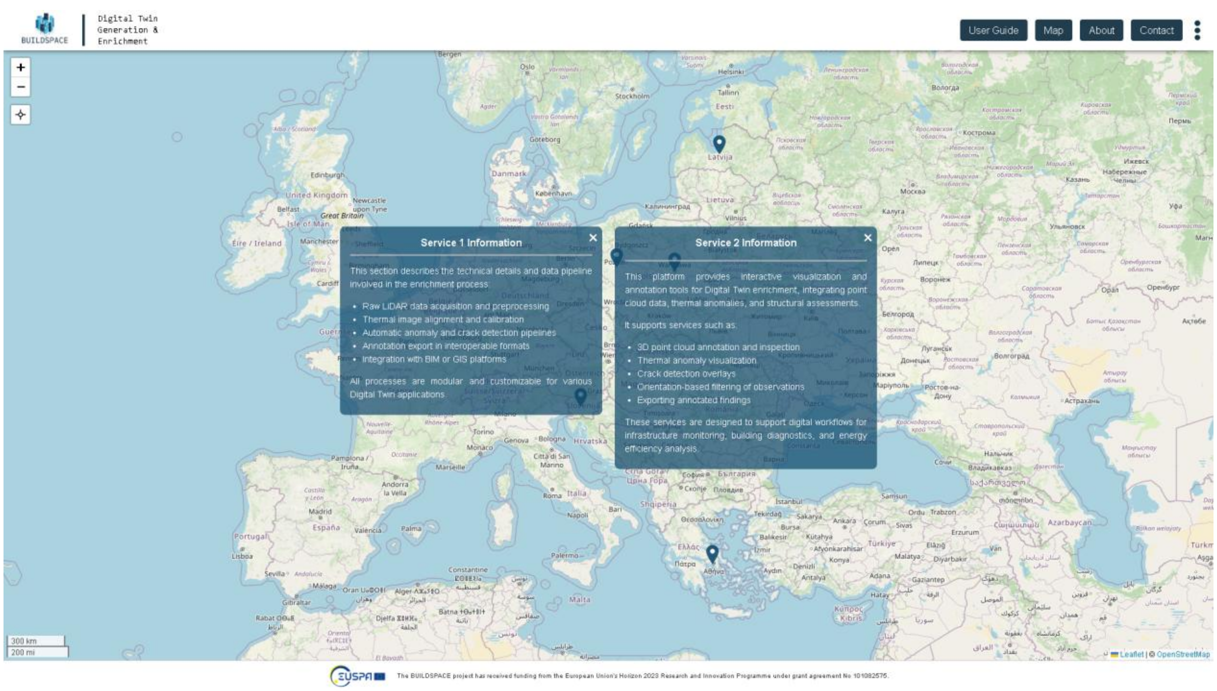


Figure 23. SE1 and SE2 main page (developed by UPM)

To provide a seamless user experience, usBIM[9] and usBIM.GeoTwin[10] are adopted to support the visualization in SE1. This platform is recommended by buildingSMART[11], an international organization that develops and maintains open standards for the digital transformation of the built environment, including the widely used IFC format. The key visualisation functionalities implemented in SE1 are introduced below.

The **2D map interface** (Figure 24 and Figure 25) displays the locations of five buildings across four pilot projects. Taking Pilot 4-IMZI as an example, the building can be navigated by selecting it from the tree table on the left-hand side. As illustrated in the figure above, the GIS map can be navigated through the following steps:

1. Select the project.
2. Click the **'Navigate'** button to visualize the GIS map, which appears as a thumbnail in the bottom-right corner.
3. Click the **'Information'** button.
4. View the corresponding EGNSS geolocation information.
5. Click the **'Link'** button to access the models associated with a specific geolocation. This feature allows users to quickly retrieve and view three key components: PCD, DT and federated model integrating both PCD and DT data for comprehensive analysis

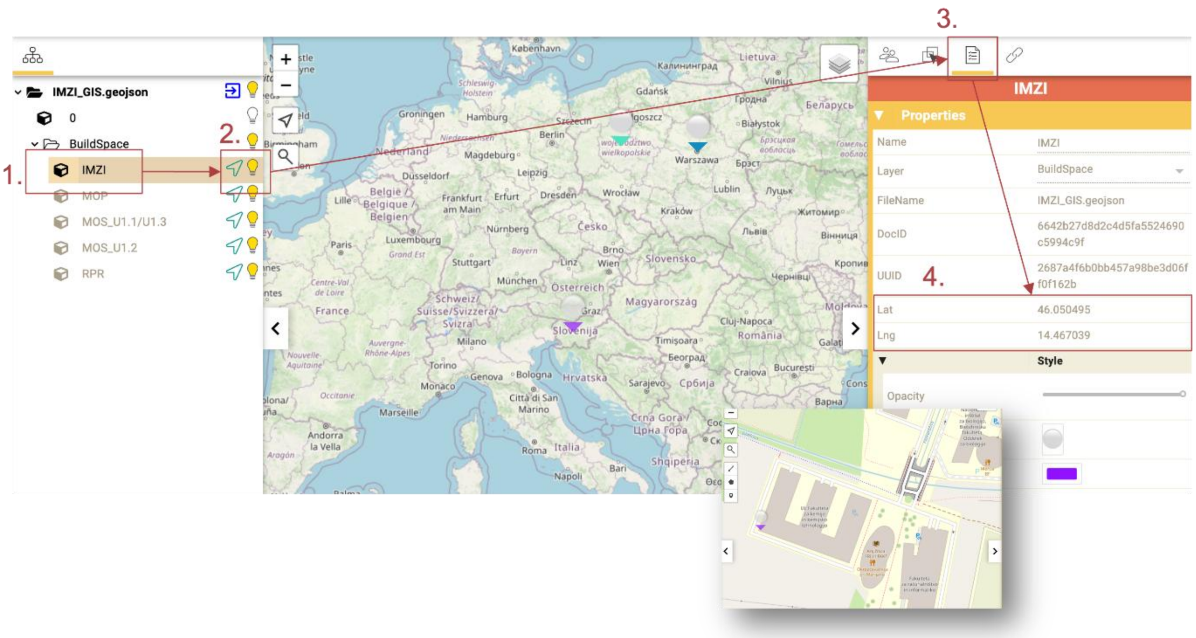


Figure 24. Navigation to pilot buildings

[9] US.BIM is part of an integrated suite of tools developed by ACCA Software, is a cloud-based, openBIM platform for the management of digital construction data of buildings and infrastructure.

[10] US.BIM.GeoTwin is an extension of the US.BIM platform, integrating geospatial data with BIM models, enabling GeoBIM and Digital Twin visualization at urban and territorial scales.

[11] https://www.buildingsmart.org/

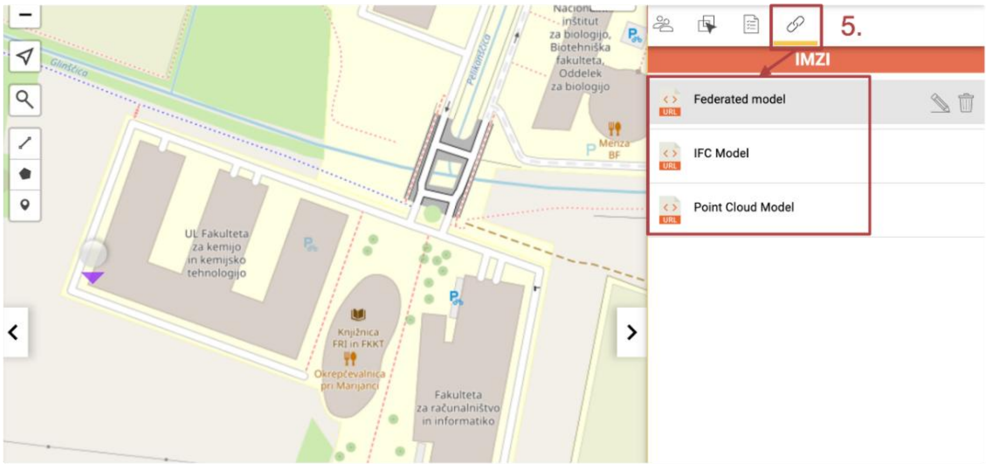


Figure 25. Link to the 3D visualisation page

The visualization of the four pilots on the 3D GIS map is not a mandatory requirement under the Grant Agreement. It may be shared via an offline document or an online link, depending on the internal technology release schedule. The **3D map interface** allows users to interactively explore the spatial location and model geometry of the selected building. As shown in the Figure 26, the navigation to the 3D model follows these steps:

1. Click on the target building icon on the map. A panel appears on the right, displaying detailed EGNSS and model metadata, including coordinates and altitude.
2. In the left-hand tree structure, locate the corresponding IFC file under the selected project folder.
3. Click the **"Zoom to model"** button to open the 3D view. This action loads the as-designed model in its actual georeferenced context and renders it within a realistic terrain environment for further inspection.

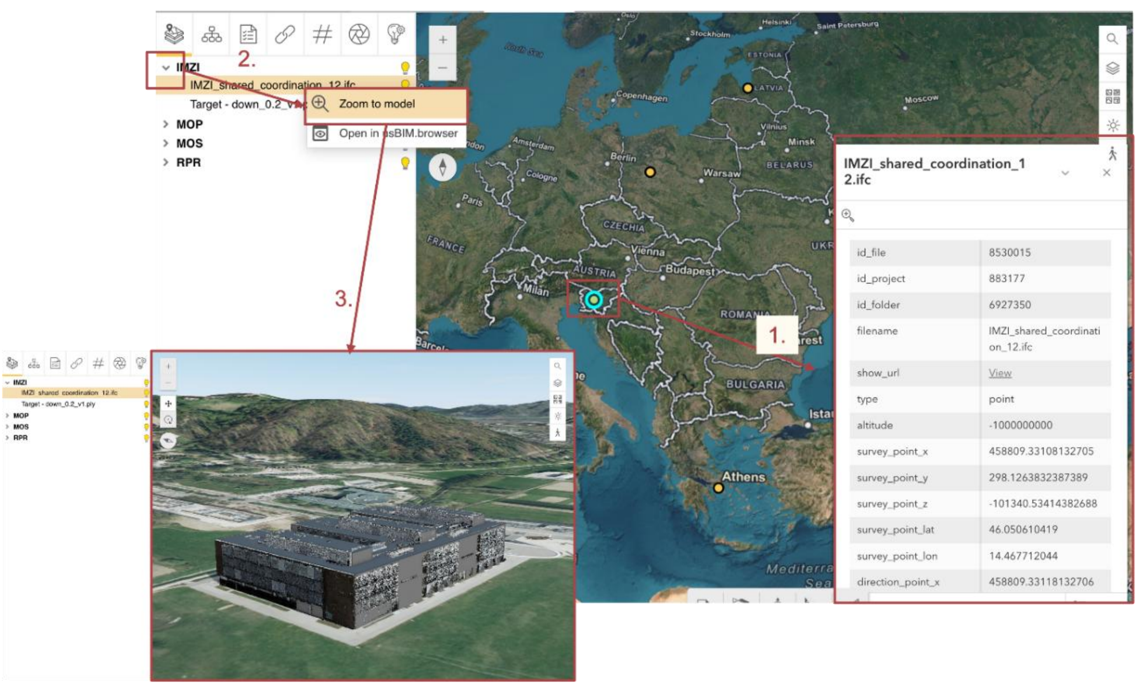


Figure 26. Check the geolocation and navigate to the buildings

The interface to visualize the building level information of 2D and 3D information is similar.

The main interface can be seen in Figure 27. It includes:

1. **Information structure of the model**: displays the hierarchical structure of the IFC model, allowing users to expand and select specific elements.
2. **Model view**: The central viewport visualizes the 3D representation of the IFC model, where users can navigate, zoom, and interact with different elements.
3. **Information upon selection**: shows detailed information about selected objects.
4. **Toolbar**: The bottom toolbar provides various tools for interacting with the model, such as measurement, sectioning, annotation, and visibility controls.

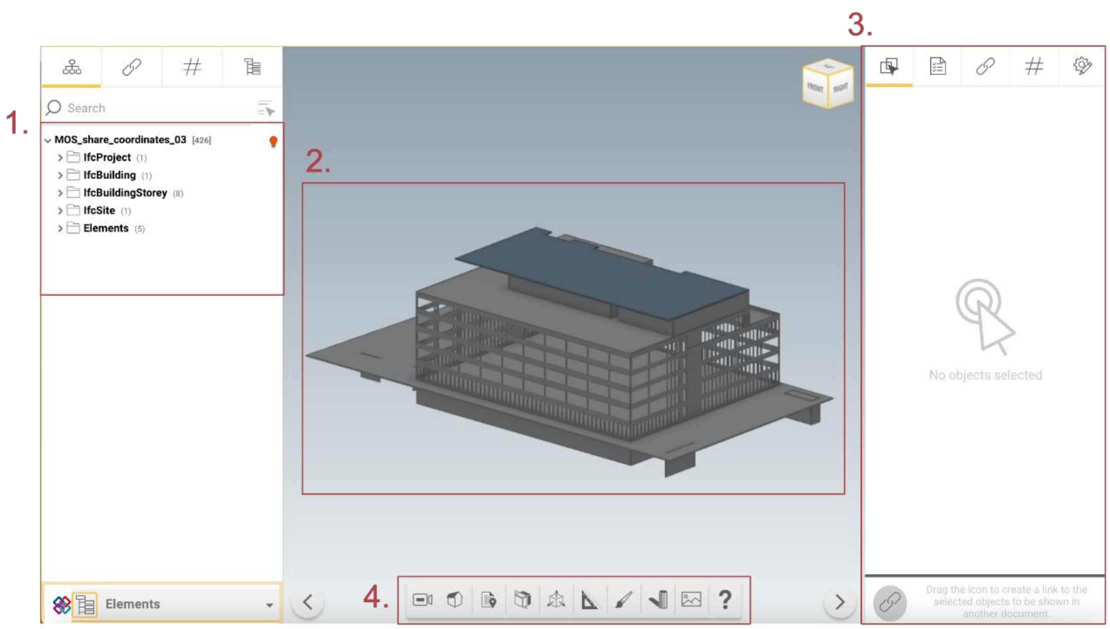


Figure 27. Main interface introduction

The **camera mode should be adjusted** (Figure 28), and selecting either the orbit mode (Figure 29) or the first-person mode (Figure 30).

- **Orbit mode**: Click the orbit icon to freely rotate around the model by clicking and dragging with your mouse.
- **First-person mode**: Select the first-person icon to navigate through the model as if walking inside, using arrow keys or mouse controls.

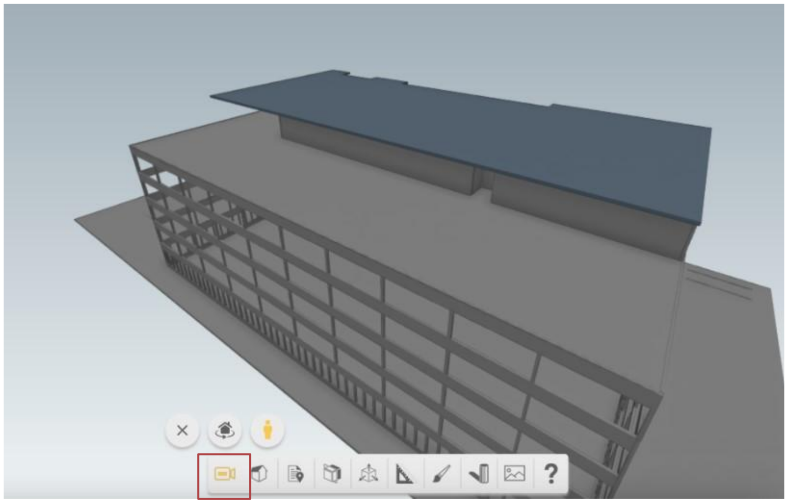


Figure 28. Adjust the camera mode

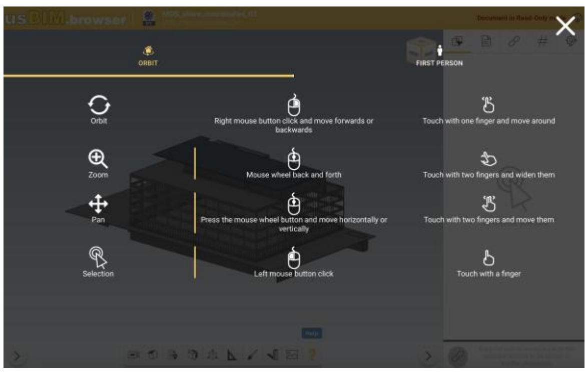


Figure 29. Orbit mode

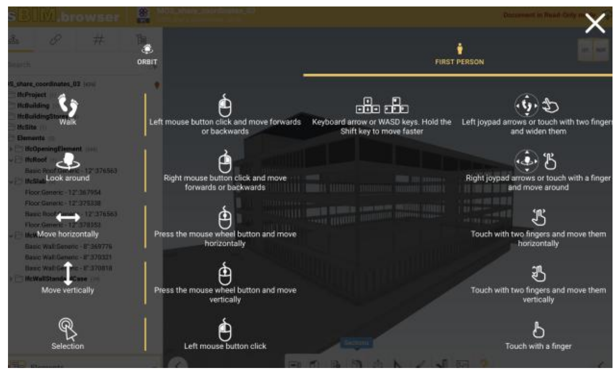


Figure 30. First-person mode

There are various ways to **view/hide specific model**. Two common-used methods are used:

1. Set the visibility through the 'bulb' button in the left-hand side bar (Figure 31).
2. Right click any element or any location of the interface to set the visibility of single or multiple elements (Figure 32).

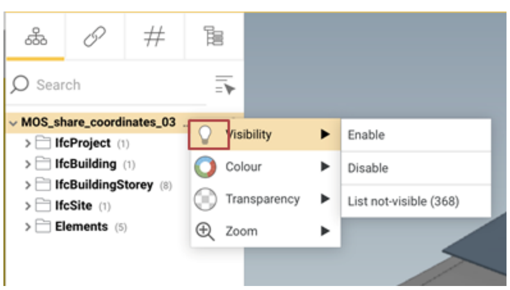


Figure 31. Set the visibility method (1.)

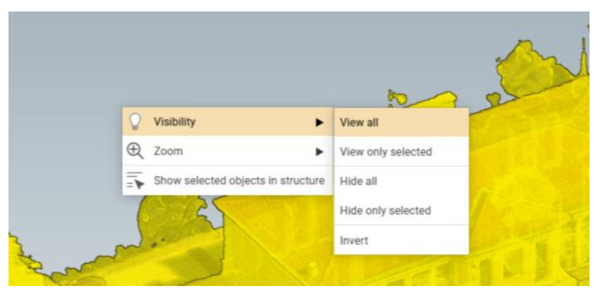


Figure 32. Set the visibility method (2.)

The **basic setting** can be seen in Figure 33. Right-click on to adjust its visibility, change its colour, set transparency levels, or zoom in on the selected object for better visualization.

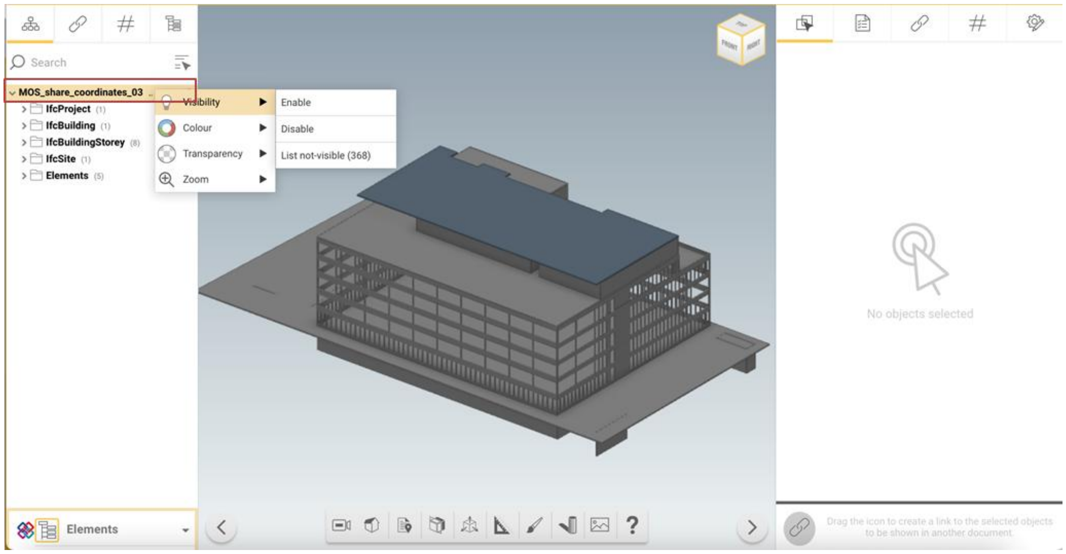


Figure 33. Basic settings

Click on an element in the 3D model to highlight it, and view its details in the right-hand panel, where you can check its properties, adjust visibility, and modify its appearance (Figure 34).

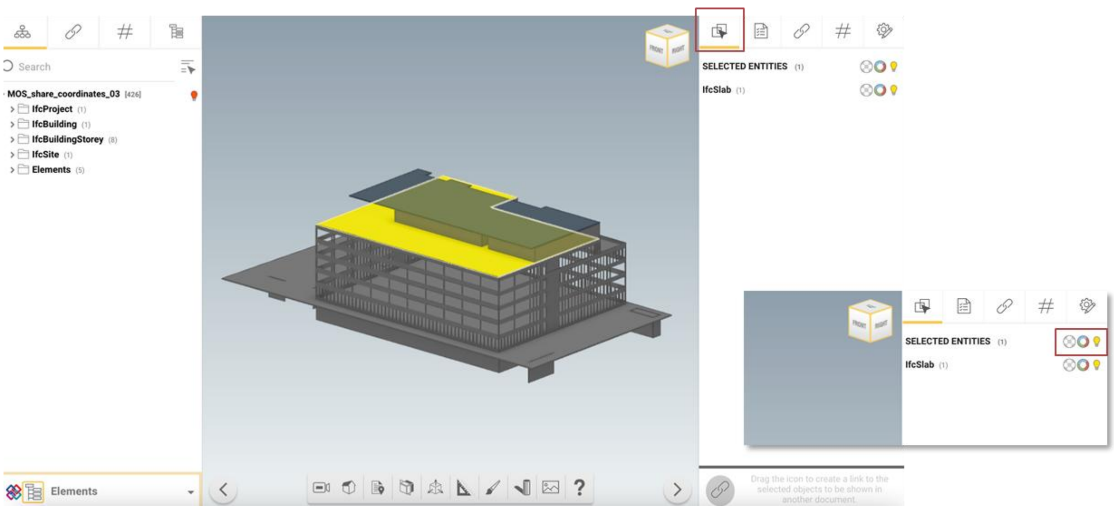


Figure 34. Select an element

Click on the **properties icon** to view detailed information about a selected element, including its type, placement, geometric representation, etc. (Figure 35).

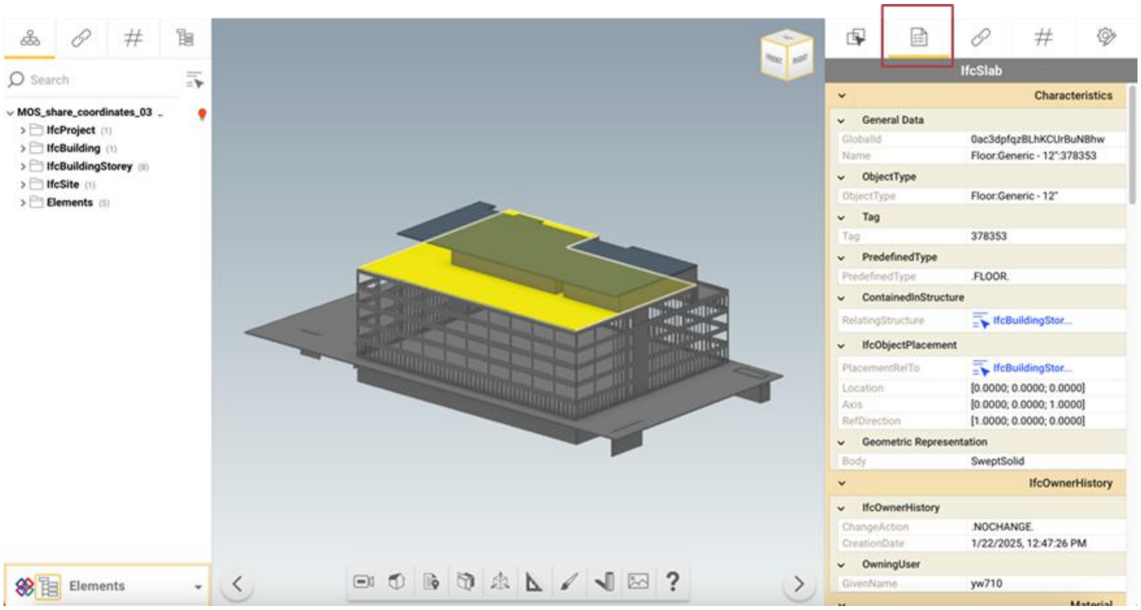


Figure 35. Check the element's properties

Click the **camera projection icon** to switch between perspective and orthographic views, adjusting how the model is displayed for better visualization and analysis (Figure 36).

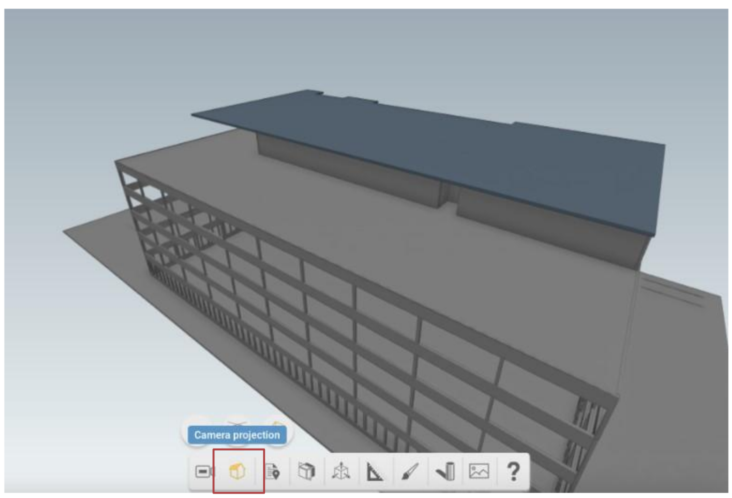


Figure 36. Adjust the camera projection

Click the section icon to **create a cutting plane**, allowing you to view and analyse the internal structure of the model by slicing through different sections (Figure 37).

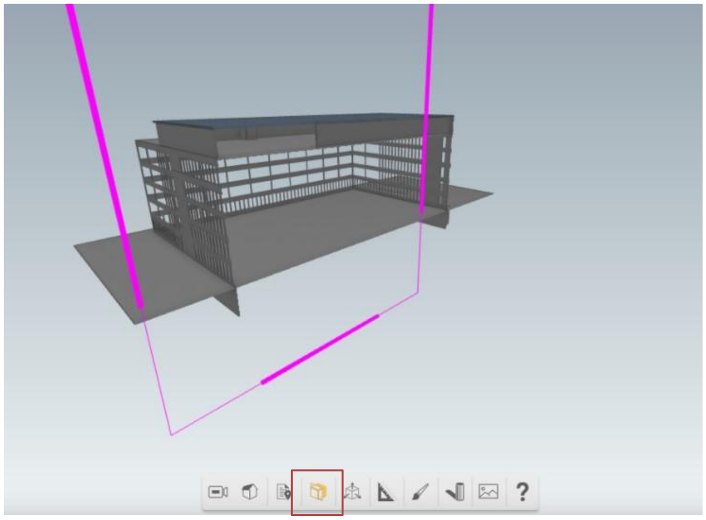


Figure 37. Create a section cutting plane

Click the **section box** icon to define a 3D clipping region, allowing you to isolate and analyse specific parts of the model by adjusting the boundaries of the section (Figure 38).

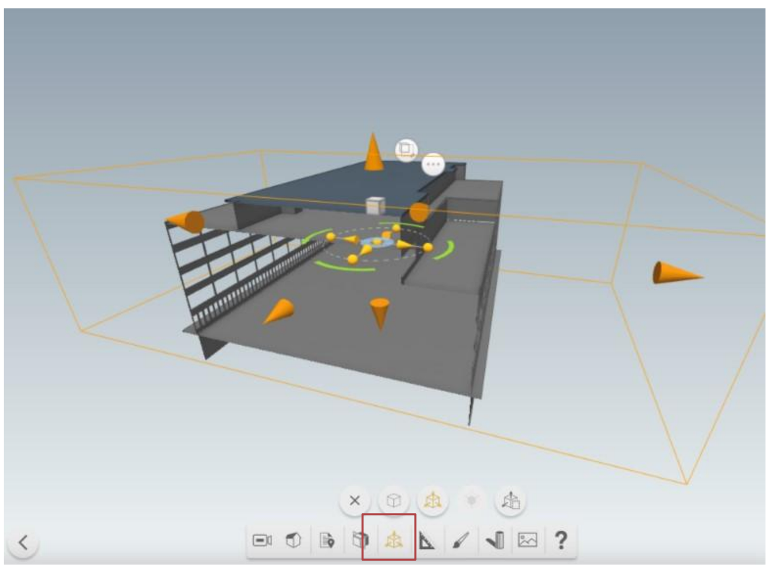


Figure 38. Create a section box

How to make a measurement can be seen in Figure 39. They could be:

- **Linear Measurements:** Use the linear measurement tool to measure distances between two points on the model.
- **Measurement of Angles:** Select the angle measurement option to show the angle between two intersecting elements or surfaces.
- **Measurement of Surface Area:** draw a surface to measure its total area, helping to analyze material quantities.
- **Show Coordinates of a Point:** Select a specific point in the model to display its exact coordinates within the 3D space.

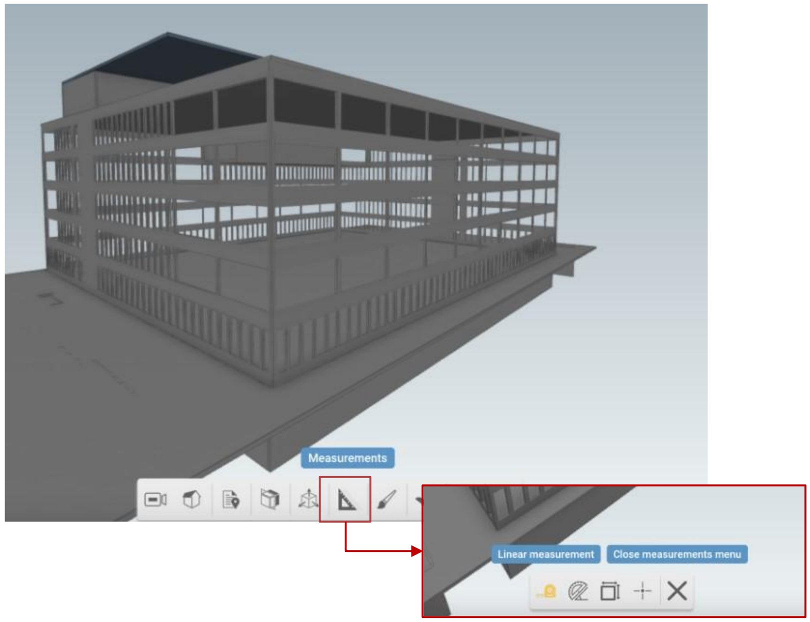


Figure 39. Make a measurement

3.3.Adaptation to pilots

To unify the diverse pilot projects under a single technical pipeline, SE1 implemented multiple strategies to address the key challenges encountered. These challenges span both the DT Generation and DT Enrichment processes. This section identifies and discusses three primary challenges, which are inconsistent data sources, incomplete data, and drone flight limitations, along with the corresponding solutions developed to overcome them.

Inconsistent data

Inconsistent data sources and varying architectural styles represent two of the most significant challenges in the DT generation workflow. These challenges arise because different scanning technologies, such as terrestrial laser scanners, airborne LiDAR, and drone photogrammetry, produce PCD with varying resolutions, noise levels, and coverage. Meanwhile, architectural diversity introduces variations in structural geometry, material properties, and feature patterns, which can limit the generalizability of ML models trained on uniform datasets.

Semantic segmentation refers to the process of classifying each point in a point cloud into predefined categories (e.g., wall, window, roof, floor), enabling meaningful structural understanding and subsequent geometric or semantic reconstruction in DT models. Existing research on automatic PCD segmentation often focuses on datasets captured from specific environments or architectural types, limiting adaptability across diverse building contexts. For instance, commonly used datasets such as S3DIS (Stanford Large-Scale 3D Indoor Spaces Dataset) and Semantic3D are tailored to indoor office spaces or urban outdoor environments, respectively. These datasets, while useful, do not fully represent the architectural complexity found in real-world, heterogeneous building stocks. In SE1, various segmentation models were tested using multiple training datasets to enhance robustness and adaptability.

Additionally, to address these challenges, a custom dataset was developed based on one of the pilot projects—specifically, the city-level LiDAR data from Riga. The target building in the Riga pilot features a classical architectural style, which is similar to that of the target building in the Piraeus pilot. As a result, a Riga façade dataset was specifically created to support segmentation and model training for this context.

The Riga dataset comprises 17 files, totalling approximately 10.2 GB in size. It includes five semantic categories: building elements, ground, roof, wall, and others. This dataset was designed to enhance segmentation performance by providing representative and context-specific samples aligned with the architectural characteristics of the pilot site. As illustrated in the figure below, a sample of the Riga façade dataset is presented to demonstrate the data structure and label distribution.

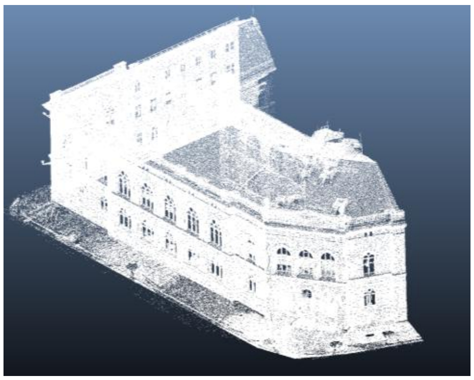


Figure 40. Raw PCD in Riga dataset

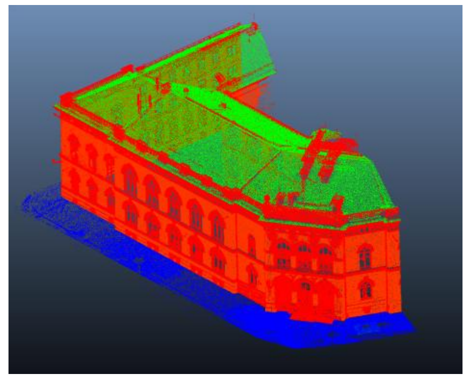


Figure 41. Segmented PCD in Riga dataset

The trained network was subsequently tested on the remaining three pilot projects: **Pilot 1 – Poland**, **Pilot 3 – Piraeus**, and **Pilot 4 – Ljubljana**, as shown below:

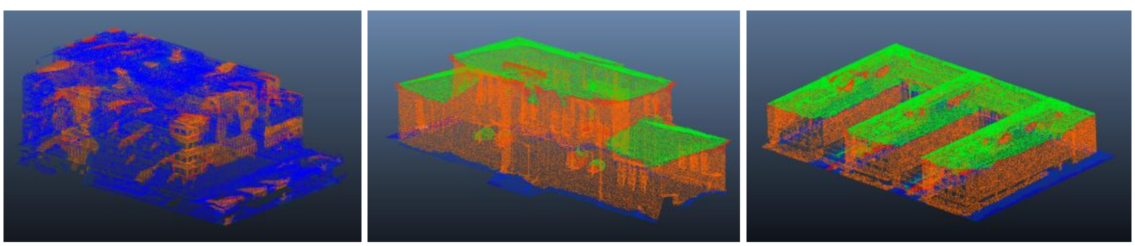


Figure 42. Trained network tested in the Pilot 1 (Poland), Pilot 3 (Piraeus) and Pilot 4 (Ljubljana) respectively

The model demonstrated promising results on the Piraeus and Ljubljana pilots, largely due to the architectural similarity between its buildings and those in the training dataset (Riga façade dataset). However, the performance was less satisfactory for the Poland pilot, due to greater architectural variation and contextual differences.

Incomplete data

Manual intervention is required between the point cloud segmentation and geometric information extraction stages to ensure higher-quality results in DT generation. While drone flights offer an efficient means of capturing the building's as-is condition, the resulting data typically lacks the resolution and accuracy achieved through LiDAR scanning, particularly in lower sections such as the ground floor as illustrated in the images below. Moreover, the quality of drone-captured data is highly dependent on environmental factors, especially lighting conditions, which can significantly affect the completeness and clarity of the point cloud.

Due to these limitations, manual adjustments are often necessary to correct or supplement missing or imprecise data, making them a critical component of the workflow. These challenges highlight why the DT generation process cannot yet be fully automated, especially when adapting to varied building typologies and data collection conditions.

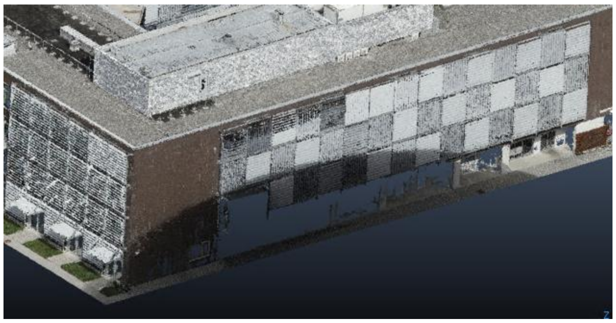


Figure 43. Ground floor data in Pilot 1 – MOS (Poland)

Figure 44. Ground floor data in Pilot 4 – IMZI (Ljubljana)

Drone flight limits

In the context of DT updates, accurate detection of construction progress is a critical component of this test scenario. Existing DT and PCD-based monitoring methods typically rely on either image-based computer vision techniques or point proximity metrics. Due to the limited availability of labelled training datasets for construction elements, this case primarily adopts a point proximity-based analysis.

However, the nature of drone-based data collection introduces key limitations. Drones can only capture the visible surface geometry of a building at the time of flight. As a result, structural elements that are partially or fully occluded, such as those covered by scaffolding, upper floors, or temporary installations, may not be detected. This limitation poses a significant challenge for relying on single-flight data to assess construction completeness.

To address this, the team developed an integrated, multi-temporal detection method. Instead of analysing each PCD in isolation, this method aggregates and compares data from multiple drone scans over time, enabling the system to infer the construction status more reliably by considering cumulative visibility across different time points.

Importantly, the detection results do not only reflect whether a building element is constructed, but also record the associated scanning date, providing a timestamped update for each component. This chronological tracking allows for more accurate progress monitoring, even in the presence of occlusions or incomplete scan data, by aligning detection results with the construction timeline.

3.4.Technical developments – Final version

This section outlines the core technical solutions implemented across the four pilot cases in SE1. These solutions are designed to address the key stages of the workflow, including DT generation, DT updates, geolocation integration, and visualization for each pilot.

While the overall methodology remains consistent, each pilot focuses on different aspects of the technical solution. Specific techniques and processes are adapted or emphasized based on the unique conditions and requirements of each pilot site. Table 7 provides a summary of how each technical solution is applied across the pilots.

The subsequent sections present detailed explanations of the algorithms and workflows adopted in each case study, demonstrating the practical application of advanced technologies that enable the successful delivery of SE1. Visualization results for different building environments will be accessible through the LINK, with the corresponding source code available via this LINK.

Table 7. DT solutions (Services 1 and 2) applied to the different pilots

Solution	Pilot 1 – Poland (UC1.1)	Pilot 1 – Poland (UC1.2)	Pilot 2 – Riga	Pilot 3 – Piraeus	Pilot 4 – Ljubljana
DT Generation					
DT Updates					
Geo-location integration					
Visualisation (screen-mode)					
Visualisation (MR-mode)					

The different techniques are detailed in the following subsections 3.4.1 and 3.4.2.

3.4.1.DT generation

The key steps in the DT generation section are the PCD semantic segmentation, extracting the geometric information and IFC creation.

3.4.1.1.PCD semantic segmentation

The first step in the automated point cloud segmentation process is the preparation of the training dataset. In this study, three buildings were selected as the primary sources: the RPR building, the building in the area '4411-32-32', and 'Ratsnams'. These buildings represent classic façade structures and provide high-quality point cloud data, making them suitable for model training. The dataset is constructed using a custom Python class, RPRFacade, built upon the PyTorch Geometric framework. This class allows for structured loading, processing, and formatting of point cloud files (.xyz) into a machine-readable format.

The dataset preparation follows the main steps of Table 8.

Table 8. Dataset preparation process for DT generation (SE1)

Dataset preparation process

```
# 1. Scan the folder and list all raw .xyz files
for file in folder:
    if file.endswith('.xyz'):
        add_to_raw_file_list(file)
```

```
# 2. For each file, load the point cloud data
for file in raw_file_list:
    data = load_txt_file(file)  # x, y, z, label
```

Dataset preparation process
if data has 4 columns: *pos = data[:, :3]   # Extract 3D coordinates* *label = data[:, 3]   # Extract semantic labels* *convert to PyTorch tensors* *create Data(pos, label)*
 # 3. *Apply optional pre-processing (filtering, transformation)* *if pre_filter exists:* *filter(data)* *if pre_transform exists:* *transform(data)*
 # 4. *Split into train/test sets* *train_data = first 80% of data_list* *test_data = remaining 20%*
 # 5. *Save the dataset* *save(train_data, 'train.pt')* *save(test_data, 'test.pt')*

This pseudo code simplifies the logic used in the full RPRFacade class implementation. It processes raw .xyz point cloud files into Data objects containing 3D coordinates and corresponding semantic class labels. After optional pre-filtering and transformation, the data is split into training and testing sets (80/20 split) and saved as .pt files for efficient use in downstream model training.

To perform semantic segmentation of façade point clouds, a customized implementation of PointNet++ is adopted, designed for classifying 3D points into structural categories such as walls, windows, roofs, etc. This model leverages hierarchical feature learning and feature propagation using the PyTorch Geometric framework. PointNet++ is an advanced deep learning architecture specifically designed for learning representations from unordered 3D point cloud data. It is an advanced model, extending the original PointNet model by incorporating a hierarchical feature learning structure that captures both local and global geometric features, making it especially effective for tasks like semantic segmentation, object recognition, and scene understanding.

Key component of PointNet++ are presented in Table 9.

Table 9. Key component of PointNet++ for SE1

Component	Description
Set Abstraction (SA) Layers	Downsample the point cloud and extract local features from grouped neighbourhoods using mini-PointNets.
Feature Propagation (FP) Layers	Upsample and interpolate features from the abstracted levels back to the original resolution for dense per-point prediction.
MLP Layers	Fully connected layers that map learned features to output classes (e.g., wall, window, roof).
Skip Connections	Preserve fine-grained details by combining low-level and high-level features across the hierarchy.

Key codes and workflow of PointNet++ are listed in Table 10.

Table 10. Key codes and workflow of PointNet++ for SE1

1. Dataset loading and augmentation

train_dataset = RPRFacade(..., split='train', transform=..., pre_transform=...)
test_dataset = RPRFacade(..., split='test', ...)

The pipeline begins by loading pre-annotated point cloud data (in .xyz or .ply format), applies geometric augmentations such as rotation and jittering to enhance robustness, and then utilizes the PyTorch Geometric DataLoader to batch and feed the data into the model for training or inference.Loads pre-annotated point cloud data (in `.xyz` or `.ply` format).

2. Model architecture: Net Class

a) SA layers

self.sa1_module = SAModule(...)
self.sa2_module = SAModule(...)
self.sa3_module = GlobalSAModule(...)

b) FP layers

self.fp3_module = FPModule(...)
self.fp2_module = FPModule(...)
self.fp1_module = FPModule(...)

c) Final MLP classifier

self.mlp = MLP([128, 128, 128, num_classes], ...)

The segmentation model is composed of three major parts:

a) SA layers

- These layers downsample and encode features from increasingly larger neighborhoods.
- Input: raw 3D coordinates.
- Output: higher-level local and global features for each point cluster.

b) FP layers

- These layers upsample and propagate features back to the original resolution.
- Combines features from earlier SA layers to reconstruct per-point feature vectors.

c) Final MLP classifier

- Predicts a semantic label for each point using a multi-layer perceptron.
- Output: Log-probabilities (log_softmax) over semantic classes.

3. Model forward pass

out = model(data)

It passes each batch of 3D points through the SA → FP → MLP pipeline, and the outputs are the scores per-point class ([N, num_classes]).

4. Training Loop
for data in train_loader: *out = model(data)* *loss = F.nll_loss(out, data.y)* *loss.backward()* *optimizer.step()*
The model is trained using the Adam optimizer with a negative log-likelihood loss function for multi-class classification, while logging loss and accuracy at each epoch.

5. Evaluation with IoU
iou = jaccard_index(pred, data.y, task="multiclass", num_classes=...)
The Jaccard Index (Intersection over Union) is computed between predictions and ground truth. The result is the mean IoU value across all test samples.

6. Model Checkpointing
torch.save({ *'epoch': epoch,* *'model_state_dict': model.state_dict(),* *...* *}, PATH)*
It saves the model and optimizer state after each epoch for reproducibility and fine-tuning.

3.4.1.2.Geometric information extraction

Based on the segmented PCD, key building components such as walls, windows, and roofs can be identified. RANSAC (Random Sample Consensus) is mainly used in this process. RANSAC is a robust algorithm commonly used to estimate mathematical models from a dataset that contains outliers—inaccurate or irrelevant data points that could distort the result. In the context of point cloud processing, RANSAC is widely used to detect geometric primitives, such as planes, cylinders, or spheres, from 3D data.

Take wall as the example, Figure 45 illustrates the geometric information extraction workflow.

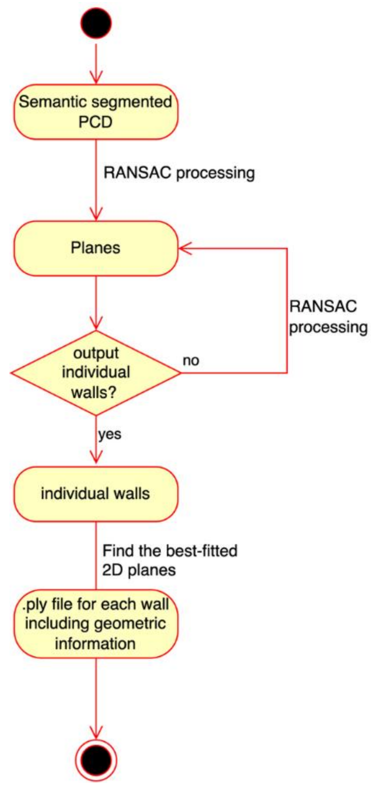


Figure 45. Geometric information extraction workflow

1. **Semantic segmentation input**: The process begins with the semantically segmented PCD, where each point has been classified (e.g., wall, window, roof).
2. **Plane detection via RANSAC**: The first geometric processing step applies the algorithm to detect planar surfaces within the point cloud. These planes typically represent large, flat surfaces such as walls or roofs.
3. **Iterative refinement**: If the initial RANSAC processing does not yield individual wall planes, the process loops back to re-run the plane detection step. This ensures that sufficient planes are identified to represent individual building components.
4. **Wall separation**: Once individual walls are successfully extracted; each wall is isolated as a distinct entity for further processing.
5. **2D plane fitting**: For each identified wall, the best-fitted 2D boundary is computed. This step refines the wall geometry, allowing for accurate representation of its shape and orientation.
6. **Output generation**: Finally, for each individual wall, a .ply file is generated. This file includes the derived geometric information.

The pseudo code of the employed RANSAC algorithm is introduced in this section. The algorithm segments one dominant plane at a time from the PCD and repeats this process iteratively. Each detected plane is saved for further use (e.g., DT geometry generation), and inliers are removed before the next iteration. After planar surfaces (e.g., walls) are extracted using RANSAC from the point cloud data, further instance-level segmentation is required to isolate individual wall components. This step is necessary because a single plane may contain multiple walls (e.g., along a long facade), and DT construction often requires element-level modelling.

Key steps and code logic are detailed in Table 11.

Table 11. Key steps and code logic for geometric information extraction

1. Load each RANSAC-extracted plane
pcd = o3d.io.read_point_cloud(input_file) *points = np.asarray(pcd.points)*
The script begins by reading .ply files generated during RANSAC-based plane segmentation. It converts the 3D coordinates into a NumPy array for clustering.
2. Apply DBSCAN clustering
dbscan = DBSCAN(eps=0.3, min_samples=5) *labels = dbscan.fit_predict(points)*
DBSCAN groups points into clusters based on density, defined by: • eps: maximum distance between two points to be considered in the same neighbourhood. • min_samples: minimum number of points required to form a dense region. •
3. Filter and save individual wall instances
for cluster_id in unique_labels: *if len(cluster_points) < min_cluster_size:* *continue* *cluster_pcd = o3d.geometry.PointCloud()* *cluster_pcd.points = o3d.utility.Vector3dVector(cluster_points)*
Each cluster is treated as a potential individual wall. To avoid noise and small artefacts, clusters with fewer points than min_cluster_size (e.g., 50 points) are discarded. Valid clusters are converted back into Open3D point cloud objects and saved as separate .ply files.
4. Batch processing multiple plane files
batch_process_ply_files(input_folder, output_folder, eps=0.3, min_samples=5, min_cluster_size=50)
The script automatically applies the DBSCAN clustering to all .ply files in the input_folder. Resulting wall instances are saved in the output_folder with unique filenames (e.g., plane_01_01.ply, plane_01_02.ply, etc.).

3.4.1.3.IFC creation

Based on the geometric data extracted from each building element, customized obj2ifc and txt2ifc algorithms are developed.

The **obj2ifc method** converts detailed 3D geometry from an .obj file into a semantically structured IFC model. It is especially useful for modelling irregular building components—such as roofs—where each surface cannot be represented using simple rectangles or two-point approximations. The algorithm preserves full mesh fidelity by using a tessellated IFC representation. The main steps and corresponding implementation logic are in Table 12.

Table 12. Key steps and code logic for IFC creation (obj2ifc)

1. Initialize IFC File from Blueprint

```
ifc = ifcopenshell.open(blueprint)
ifcNew = ifcopenshell.file(schema=ifc.schema)
project = ifc.by_type("IfcProject")[0]
context = ifc.by_type("IfcGeometricRepresentationContext")[0]
floor = ifc.by_type("IfcBuildingStorey")[0]
```

A new IFC file is created based on a predefined template (blueprint). Essential entities such as IfcProject, IfcOwnerHistory, IfcGeometricRepresentationContext, and IfcBuildingStorey are extracted from the blueprint and added to the new file.

2. Create IFC geometry from mesh

```
point_list = new_ifc.createIfcCartesianPointList3D()
point_list.CoordList = v
faces = [new_ifc.createIfcIndexedPolygonalFace(face) for face in fx]
faceset = new_ifc.createIfcPolygonalFaceSet()
faceset.Faces = faces
faceset.Coordinates = point_list
```

The vertex list from the OBJ file is converted into an IfcCartesianPointList3D, and each face is wrapped into IfcIndexedPolygonalFace elements. These are grouped together into an IfcPolygonalFaceSet, which accurately represents the tessellated roof geometry.

3. Define object placement

```
B1_Point = new_ifc.createIfcCartesianPoint((0.0, 0.0, 0.0))
B1_Axis2Placement = new_ifc.createIfcAxis2Placement3D(B1_Point)
B1_Placement = new_ifc.createIfcLocalPlacement(container.ObjectPlacement, B1_Axis2Placement)
```

The spatial placement of the roof object is defined using IfcLocalPlacement and IfcAxis2Placement3D, ensuring that the geometry is correctly positioned relative to its parent building storey.

4. Create roof entity with tessellated shape

```
B1 = new_ifc.createIfcRoof(create_guid(), owner_history, "roof")
B1_Repr = new_ifc.createIfcShapeRepresentation()
B1_Repr.RepresentationType = 'Tessellation'
B1_Repr.Items = [faceset]
B1_DefShape = new_ifc.createIfcProductDefinitionShape()
B1_DefShape.Representations = [B1_Repr]
```

B1.Representation = B1_DefShape *B1.ObjectPlacement = B1_Placement*
An IfcRoof entity is created and linked to the geometry using an IfcShapeRepresentation and IfcProductDefinitionShape, with the representation type set as 'Tessellation' to preserve the mesh structure.
5. Link Roof to Building Storey
Flr1_Container = new_ifc.createIfcRelContainedInSpatialStructure(create_guid(), owner_history) *Flr1_Container.RelatedElements = [B1]* *Flr1_Container.RelatingStructure = container*
The roof element is then associated with its spatial container (building storey) using IfcRelContainedInSpatialStructure, maintaining semantic integrity within the building hierarchy.

Next, there is **txt2ifc.** The creation of an IFC model from .txt file is based on ifcopenshell, focusing on constructing a building hierarchy and adding geometry for walls and openings (Table 13). The code is structured to handle both reading geometry data from external files and generating the appropriate IFC entities for a building's walls and openings.

Table 13. Key steps and code logic for IFC creation (txt2ifc)

1. IFC Project Template Setup
temp_handle, temp_filename = tempfile.mkstemp(suffix=".ifc") *with open(temp_filename, "wb") as f:*   *f.write(template.encode("utf-8"))* *ifcfile = ifcopenshell.open(temp_filename)*
This step creates a minimal IFC template using a string template compliant with IFC2X3. It initializes entities such as IfcProject, IfcOwnerHistory, IfcGeometricRepresentationContext, and units (length, area, volume). The template is written to a temporary file and then loaded with \`ifcopenshell.open()\`.
2. Hierarchical IFC Structure Creation
site_placement = create_ifclocalplacement(ifcfile) *site = ifcfile.createIfcSite(...)* *building_placement = create_ifclocalplacement(ifcfile, relative_to=site_placement)* *building = ifcfile.createIfcBuilding(...)* *storey_placement = create_ifclocalplacement(ifcfile, relative_to=building_placement)* *building_storey = ifcfile.createIfcBuildingStorey(...)*
Create a building hierarchy with Site, Building, and BuildingStorey elements using \`create_ifclocalplacement()\` to define spatial relationships. The building structure is created top-down.
3. Wall Generation from TXT Geometry
bottom_profile = [A.tolist(), B.tolist(), C.tolist(), D.tolist(), A.tolist()]

height = float((facade_points[0] - facade_points[1])[2])
solid = create_ifcextrudedareasolid(...)
wall = ifcfile.createIfcWallStandardCase(...)

Walls are generated from 3D coordinates stored in a .txt file. Four points define the wall face, and the profile is extruded to form a solid wall using `IfcExtrudedAreaSolid`.

4. Material, Property, and Quantity Assignment

material = ifcfile.createIfcMaterial("wall material")
property_set = ifcfile.createIfcPropertySet(...)
element_quantity = ifcfile.createIfcElementQuantity(...)
ifcfile.createIfcRelDefinesByProperties(...)
ifcfile.createIfcRelAssociatesMaterial(...)

Materials (e.g., wall material), property sets (like IsExternal), and quantities (e.g., area, volume) are defined and linked to the wall using `IfcRelAssociatesMaterial` and `IfcRelDefinesByProperties`.

5. Openings and Windows from Rectangle Files

```
for op in all_openings:
    opening_name, opening_points = list(op.items())[0]
    create_opening_and_window(ifcfile, opening_name, window_name, opening_points)
```

Openings and windows are defined for each wall using a structured loop over `rectangle_txt` files. Each .txt file contains four 3D coordinates representing rectangular windows or openings. Both `IfcOpeningElement` and `IfcWindow` are created and linked to the wall.

3.4.2.DT updates

The workflow of the DT updates (Figure 46) represents a process for tracking construction progress using an as-designed IFC model with scheduled construction and multiple PCDs that are captured during the construction progress.

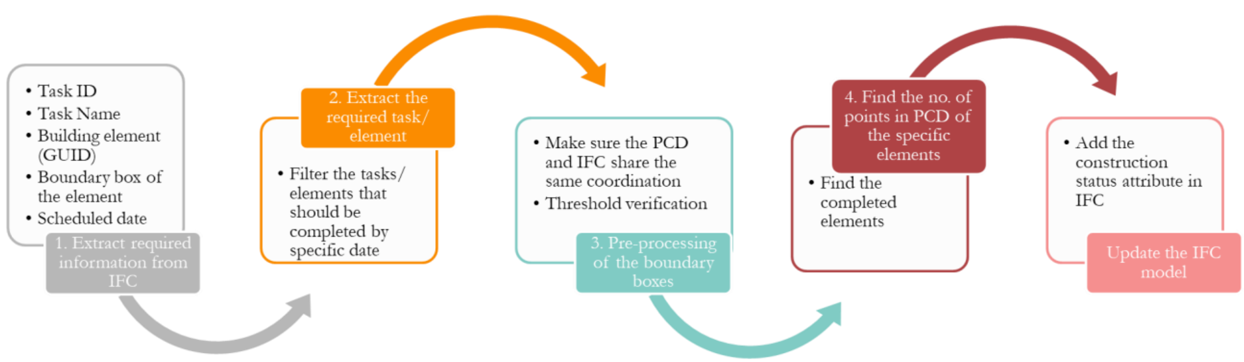


Figure 46. Workflow of updating the gDT

The first step in the process involves extracting the necessary information from the IFC model, which is a central data model used for managing building information. Key details that are extracted include the task ID, task name, the unique building element identifier (GUID), the boundary box that defines the spatial limits of the building elements, and the scheduled completion date for each task. This information is essential to define the scope of what needs to be analysed in terms of construction progress, providing a structured data set for further analysis.

Once the relevant information is extracted, the next step is to filter the tasks and elements to identify which ones should have been completed by a specific date. This filtering ensures that only the tasks that are relevant to the current construction milestone are included in the analysis. By focusing on scheduled tasks, the system can streamline the assessment process and prioritize the elements that should be examined for completion.

In the third step, pre-processing is performed on the boundary boxes of the building elements to ensure that the PCD and the IFC model share the same coordinate system (Figure 47). Additionally, a threshold verification is applied to account for tolerances, ensuring that small deviations in the data do not lead to incorrect results. This pre-processing step guarantees the integrity and accuracy of the data before progressing to further analysis. Figure 47 shows the mapping between boundary boxes extracted from IFC elements with the point cloud model captured during the construction timeline.

Figure 47. Mapping between the IFC elements and construction point cloud data – Polish pilot

After the pre-processing, the system proceeds to count the number of points in the PCD that correspond to the specific elements extracted from the IFC model. The presence of sufficient points in the PCD within the boundary box of a building element indicates that the element has been completed. This step is vital for identifying completed elements by analysing the actual construction progress on-site, as represented by the point cloud data.

Finally, the IFC model is updated with the construction status of each element. For those elements identified as completed, the system adds the relevant status attribute to the IFC model. This step keeps the model synchronized with real-time construction data, ensuring that project managers and stakeholders have an accurate and up-to-date representation of the building's progress. By updating the model, the system provides a clear and dynamic picture of which tasks have been completed and which are still in progress, enabling better project tracking and decision-making (Figure 48).

```
Element with GUID 0SOqSLgbL02vPmfn23gVOG updated: Status -> Undetected, UpdatedDate -> 27 May 2024
Element with GUID 2a_JwKAhX2weU_5bcIMExQ updated: Status -> Undetected, UpdatedDate -> 27 May 2024
Element with GUID 1KVzLToTr72QLldg3nbiUE updated: Status -> Undetected, UpdatedDate -> 27 May 2024
Element with GUID 3qc2tbh2P1ORSe6o5E_8MS updated: Status -> Undetected, UpdatedDate -> 27 May 2024
Element with GUID 1rO_LfDWz3mQvxfPXc_EmX updated: Status -> Undetected, UpdatedDate -> 27 May 2024
Element with GUID 0imi_PC7j4MAuEJxHzoRDP updated: Status -> Undetected, UpdatedDate -> 27 May 2024
Element with GUID 2gccaj68X8ghjd1tUCg5xw updated: Status -> Undetected, UpdatedDate -> 27 May 2024
Element with GUID 1ThBBWTibD8hDn4WJ4LVqw updated: Status -> Undetected, UpdatedDate -> 27 May 2024
Element with GUID 3oIQSKeTf6j8y19dgu$AWL updated: Status -> Undetected, UpdatedDate -> 27 May 2024
Element with GUID 2DtfbH0nH0uBhyLYArKv2Q updated: Status -> Undetected, UpdatedDate -> 27 May 2024
Element with GUID 10s2_cjjn2SuASzUxQpf5I updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 2a3XZXNjL2vQ$fkqNZNwLW updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 02hFqCyH1F4uh9MO3D6_Ap updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 3Ml4MMwzbBIv7USqZQCD7k updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 3PDB$tHG999Ba54vUISfna updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 0dO19sk6X7Th6UTdpS_8E4 updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 0rmMuMizb2LQJ2SrEE5BRn updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 1qIgV740PB_B$I3wCwMJt0 updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 1nwjuIFnX8FeGJwzlygR34 updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 04br$ZCoD3hRzK1n9UPqds updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 2H6FAN42XBrPGoTeqYCBbA updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 1PxBGBOEr00hcoi9CZKkbA updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 3G4Ku1rLv6q8K$NcuD27yu updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 2Btd9QWcr7Wf04$WofF4BA updated: Status -> Completed, UpdatedDate -> 27 May 2024
Element with GUID 173s7Fh5rBVQIV_f3tSeU3 already completed. Skipping.
Element with GUID 3aTwLCwBD1GvRXCoI4k_fP already completed. Skipping.
Element with GUID 3EPLue1jj5txsl1P3pjvN5 already completed. Skipping.
```

Figure 48. Logs of the construction status updating

3.5.Replication and uptake potential

SE1 focuses on transforming unstructured PCD into structured gDT representations enriched with geometric, semantic, and EGNSS geolocation information. The automated process offers significant efficiency gains in the digitalization of buildings and urban environments. While many state-of-the-art studies concentrate on isolated stages, such as semantic segmentation of PCD, geometric feature extraction (e.g., vertices and edges), or mesh creation/completion, very few have proposed an end-to-end automated workflow. SE1 addresses this gap. However, it encounters two major challenges:

1. **Data dependency of supervised ML segmentation:** Supervised machine learning-based PCD segmentation methods require high-quality, diverse datasets. Currently, there is a lack of publicly available datasets that comprehensively cover different architectural styles and building typologies.
2. **Manual interventions in automation:** Despite automation solutions that have been developed, certain tasks still require manual fine-tuning, such as parameter selection in down-sampling, cluster detection, and ML model adjustments.

The SE1 scope involves five distinct buildings, adding further complexity to developing a unified workflow. A generalizable workflow has been successfully implemented, but it still requires some manual corrections as described in section 3.2.

Nevertheless, SE1 demonstrates strong potential across other cities and contexts by:

- **ML-based semantic segmentation**: The trained ML models can be transferred to other projects for façade-level semantic segmentation. However, pre-processing of test data (e.g., noise removal) and compatibility in terms of data scale and architectural style remain prerequisites.
- **DT generation algorithm**: The algorithm effectively converts geometric data formats (e.g., .txt, .ply) to standardized .ifc models. Accurate geometric identification is essential for acceptable outcomes.
- **Visualization solution**: The USBIM platform is deployed for DT visualization. It supports visual integration of PCD, IFC, and mesh data with geolocation, and can be extended to other projects with similar needs.
- **DT updates**: The update mechanism for monitoring construction progress and integrating it into DTs is transferable. However, alignment between the captured PCD and the as-designed BIM model is crucial.

The key insights of lessons learned from the pilot deployment are:

1. **Data collection strategy**: Drone-based photogrammetry has proven to be a cost-effective and flexible approach for capturing existing building facades and roof structures. It is particularly advantageous in dense urban environments where access is limited, and large-scale scanning is needed quickly. However, the resolution and depth accuracy of data captured through photogrammetry are significantly lower compared to LiDAR-based laser scanning. Photogrammetry often struggles with occlusion, non-reflective materials, and generating clean point clouds in complex geometries. In contrast, LiDAR offers high-resolution, millimetre-level accuracy, especially for capturing fine-grained details of architectural elements. Its performance remains robust under varying lighting conditions. Therefore, when the project budget allows, LiDAR scanning is recommended for critical phases of Digital Twin generation, particularly when precise geometric reconstruction is required for downstream use cases such as structural analysis or energy simulation.
2. **Limitations of fully automated pcd-to-dt conversion**: Although SE1 incorporates multiple automated modules—from point cloud segmentation to geometric surface fitting and IFC conversion—achieving a fully automated pipeline from raw point cloud data to semantically rich, georeferenced Digital Twin models remains a significant challenge. Current state-of-the-art machine learning models, such as PointNet++, offer promising results for semantic segmentation, but they still depend heavily on well-curated, labeled datasets, which are scarce for real-world architectural contexts. Furthermore, post-segmentation steps such as mesh generation, geometry regularization, and conversion to IFC schema require context-sensitive adjustments, especially for non-standard architectural elements (e.g., irregular roofs or historical façades). Therefore, while SE1 has advanced automation at the component level, a fully hands-off workflow is not yet feasible. Human intervention remains essential for parameter tuning (e.g., down-sampling thresholds, cluster size settings), semantic validation, and ensuring the spatial consistency of converted geometry.
3. **Semantic segmentation of PCD**: The semantic segmentation of the PCD is always a challenging topic in the academics. Future improvements are expected with the release of higher-quality datasets and the evolution of advanced ML models.

4. **Interrelationships among the DT elements and their impact on updates**: One of the key use cases of SE1 is construction progress monitoring via drone data. A common method for representing progress is by color-coding different object states (e.g., completed, under construction, delayed) within the Digital Twin model. However, practical deployment reveals that such updates may lead to incorrect colour labelling if the underlying dependencies among components are not accounted for.
5. **Data collection for construction progress monitoring**: For the drone-based construction progress monitoring scenario, it we suggests that the drone flight implemented in a short interval between each flight to ensure that every element is captured.
6. **Visualization platform selection and user-friendliness**: The primary output of SE1 is the IFC-format DT, which ensures interoperability across platforms and adheres to industry standards. However, feedback from pilot stakeholders highlighted concerns regarding the usability of the IFC viewers, particularly for non-technical users. While USBIM was selected as the visualization platform in SE1 due to its compatibility and online deployment capability, the user interface, rendering performance, and interaction features (e.g., filtering elements, inspecting attributes) vary widely across platforms. This approach allows each pilot to adopt the viewer of their choice (e.g., Trimble Connect, BIMvision, xBIM, Unreal Engine-based tools), depending on project needs).

The SE1 have been tested by the pilot teams in the different development cycles. The testing results from the pilot teams can be found in the WP4 deliverable, D4.3 *Pilot's execution documentation – full-pilot phase*. The comments mainly focus on the service scope of DT generation. SE1 provides DT generation and updating services for five buildings across four pilots using both cutting-edge and custom-developed algorithms. While building a fully automatic PCD-to-IFC converter for broader use is beyond the scope of SE1. Its comprehensive workflow, including geometric reconstruction, EGNSS integration, and visualization, is considered pioneering in current practice.

In summary, SE1 delivers an integrated workflow for DT generation and updating. It has successfully produced geometric DTs and construction-aware DTs for pilot buildings, embedding spatial, geometric, and location-aware information. These outputs serve as valuable assets for downstream tasks such as thermal analysis, building operations and maintenance, and spatial analytics.

4. BUILDSPACE service SE2 – Digital Twin Enrichment (building scale)

The Digital Twin Enrichment (SE2) service is designed to provide **detailed building-scale data** using UAVs and SLAM. This service focuses on generating external building models through UAV, capturing RGB and thermal images, as well as inside models based on point clouds generated by SLAM. The integration of these data sources enables the identification and analysis of thermal anomalies in the building envelope, such as cracks, moisture, and faulty solar panels.

Service 2 includes the photogrammetric **reconstruction of RGB images** to generate 3D meshes and exterior point clouds for the pilots in Poland and Greece. Additionally, in Poland, the external point cloud is integrated with internal data obtained via SLAM, providing a comprehensive view of the building. Algorithms are being developed to **project thermal textures** onto the RGB images, resulting in models that combine both thermal and visual data for more detailed analysis.

Furthermore, the service focuses on the **semi-automated detection of critical areas** in building envelopes. This includes identifying **cracks**, detecting **malfunctional solar panels** by locating faulty cells, and recognizing **thermal anomalies** using statistical models and classification algorithms. The results of these analyses will be presented in downloadable reports, providing key information on the condition of the building envelope.

The two main objectives of SE2 are to **optimize drone flight protocols**, reducing time and data acquisition costs by efficiently capturing both RGB and thermal images, and to advance the automation of **critical area detection using artificial intelligence**. This will improve the accuracy and efficiency of building inspections, supporting the evaluation of building envelope conditions in both rehabilitation and new construction projects.

4.1.Input and output

The inputs used by SE2 are the following:

- **External envelope data:** UAV flights are used to acquire external images of the buildings, combining RGB and thermal data. The visual and thermal datasets are processed through photogrammetric techniques to generate 3D point clouds. These are used to detect surface anomalies such as cracks, thermal anomalies or defective solar panels. Topographic control is ensured through ground control points or RTK-enabled drones, providing georeferenced coordinates to align the models with high accuracy.
- **Internal envelope data:** The inner geometry of the building is captured using SLAM-based mobile mapping systems equipped with RGB sensors. The result is a detailed point cloud of the internal spaces, enabling the integration of interior conditions into the external point clouds. An overlap area between indoor and outdoor scans is ensured to achieve consistent coordinate referencing.
- **Georeferencing and alignment data:** All captured datasets are georeferenced using ground control points and real-time kinematic (RTK) GPS data to ensure spatial consistency between external and internal models. This alignment is critical for merging heterogeneous data sources into a coherent digital twin.

- **Weather and ambient conditions:** During UAV data acquisition, weather conditions such as sky clarity, ambient temperature, and humidity are recorded and complemented by local meteorological datasets. These parameters are crucial to correctly interpret thermal readings and ensure reliable detection of anomalies.

The overall structure of input integration, scenario modelling and interactive functionalities are summarised in the following Figure 49.

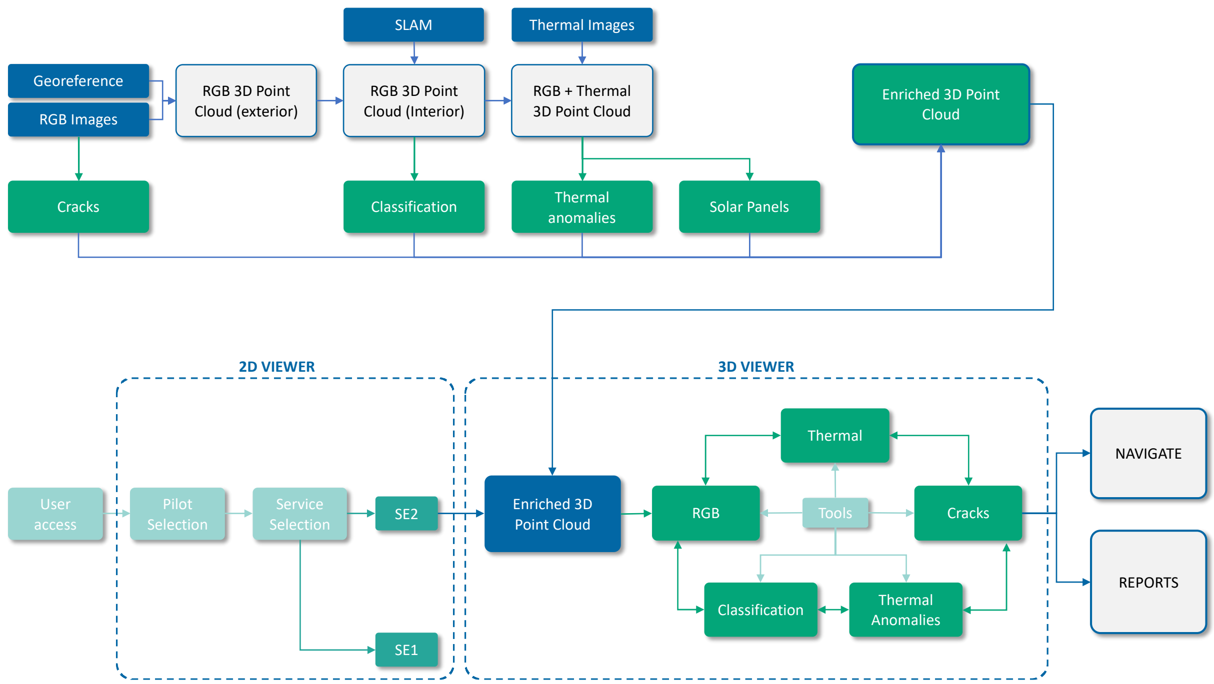


Figure 49. Workflow of SE2: data processing, scenario modelling and user interaction outputs

The outputs of SE2 are as follows:

- **RGB and thermal point clouds:** The service delivers 3D point clouds of the building's external envelope, integrating RGB and thermal information into a unified model. This output enables precise spatial analysis of the building envelope, including surface features, material textures and thermal behaviour, and forms the visual foundation for all subsequent diagnostics.
- **Semantic classification of the point cloud:** The 3D data is segmented and classified into structural and spatial components such as façades, floors, stairs, roof, and ground. This categorisation facilitates navigation, filtering, and targeted analysis within the model.
- **Detection of structural and thermal anomalies:** The service automatically identifies critical pathologies in the envelope, including cracks (via RGB data), thermal bridges and damp areas (via thermal mapping and clustering algorithms). These anomalies are spatially referenced within the 3D point cloud, allowing users to locate and assess each issue in its real-world position.
- **Solar panel diagnostics:** On buildings with photovoltaic installations, the service detects underperforming or malfunctioning panels using thermal contrast and temperature thresholds. Results are reported as anomaly maps over the rooftop surface, identifying hotspot patterns that indicate defects.

- **Interactive inspection dashboard:** All enriched data are made available through the SE2 platform, allowing users to explore the building's digital twin in an interactive 3D environment. Functionalities include switching between RGB, thermal and hybrid views, highlighting anomaly clusters, extracting façade sections, and accessing per-point temperature and reflectance values.
- **Inspection reports and annotations:** Users can generate automated reports summarising detected anomalies and conditions of interest. Reports include visual evidence, quantitative descriptors and georeferenced annotations. This supports documentation and communication of findings to stakeholders.
- Additionally, the enriched point cloud serves as a **baseline snapshot** for tracking degradation or improvements over time. By repeating the inspection under similar conditions, the service enables comparison of historical and current states for maintenance and retrofitting evaluation.

4.2.User experience

The central component of the Service 2 – Digital Twin Enrichment, developed within BUILDSPACE, is a browser-based geographic information system designed for visualization, analysis, and interaction with 3D building data.

The visualisation platform integrates high-resolution datasets such as 3D point clouds, thermal imagery, and BIM models, with GNSS-derived geolocation, offering novel services tailored for stakeholders operating in both building and urban-scale domains. Designed to support Digital Twin (DT) generation and enrichment at the building scale, the platform serves as a user-friendly access point to the DT services.

These services are accessible through a customized visualization platform connected to a pilot map, which serves as the user's navigation tool across project sites.

The key features of the interface for services 1 and 2 are:

- **Pilot map navigation:** Explore pilot buildings and test sites across Europe using an interactive map interface, with access to contextual metadata and direct links to services.
- **Integrated visualization:** Explore RGB, thermal, and classified 3D point clouds, toggle between photorealistic textures and thermal overlays, and customize display settings.
- **Measurement & inspection tools:** Measure distances and areas, generate profiles and inspect specific elements (e.g., façade details, windows, and cracks patterns).
- **Automated reports:** Crack detection and classification outputs, and thermal anomaly clustering.

The user experience of the service 2 is organised under the following aspects across the tool:

- Navigating the platform interface
- Exploring services associated with pilot locations
- Interacting with the 3D viewer tools and reports
- Troubleshooting and best practices for visual diagnostics

4.2.1.Access & navigation

The SE2 browser-based tool is designed for ease of use without requiring additional software installation.

It should be opened with a browser to enter the following public URL https://se2-buildspace.euinno.eu/.

For optimal performance, especially when using 3D visualization, it is recommended to use a device with a dedicated graphics card and a minimum screen resolution of 1366 x 768 pixels. A stable internet connection is also necessary, particularly when loading large point cloud datasets or switching between services.

The tool presents users with a map-based landing page. This interactive map serves as the main entry point to all available pilot sites and services. Locations across Europe are marked with clickable pins, each representing a BUILDSPACE pilot sites.

The map is fully interactive and supports intuitive navigation (Figure 50):

- Users can zoom in or out using the mouse scroll wheel or the zoom controls located on the left side.
- To pan across the map, users can click and drag in any direction.
- Hovering over a pin highlights the site; clicking on it opens the location's detailed information window.

Figure 50. Navigation bar

At the top of the screen, a persistent navigation bar gives access to essential resources. The "Map" button resets the view to the main landing page, allowing users to quickly return and select a new pilot site. Other menu items include "User Guide", "About", and "Contact" (Figure 51), providing easy access to documentation, platform information, and support channels.

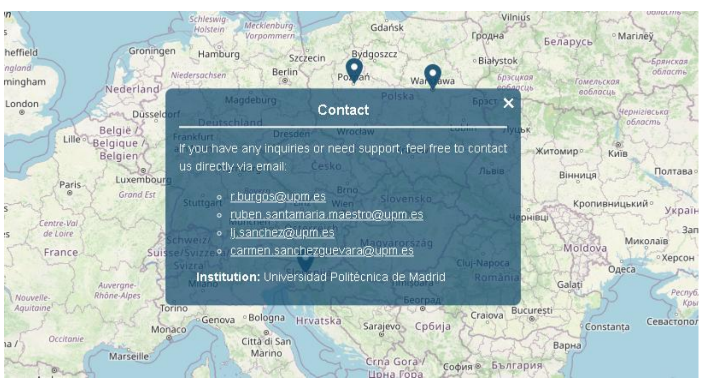


Figure 51. Contact information

The map interface is designed to be the central navigation hub of the tool. From this view, users can access all pilot data, services, and tools.

4.2.1.Tool services

Each pilot site pin opens an information panel containing descriptive metadata about the selected building. This may include the building type, number of floors, use case (e.g., academic, municipal), and any relevant technical details such as sensor deployment or structural characteristics.

The service's interface is customized to reflect the specific data available for the selected pilot site, and within the pop-up, users will find direct links to the two DT services (Figure 52).

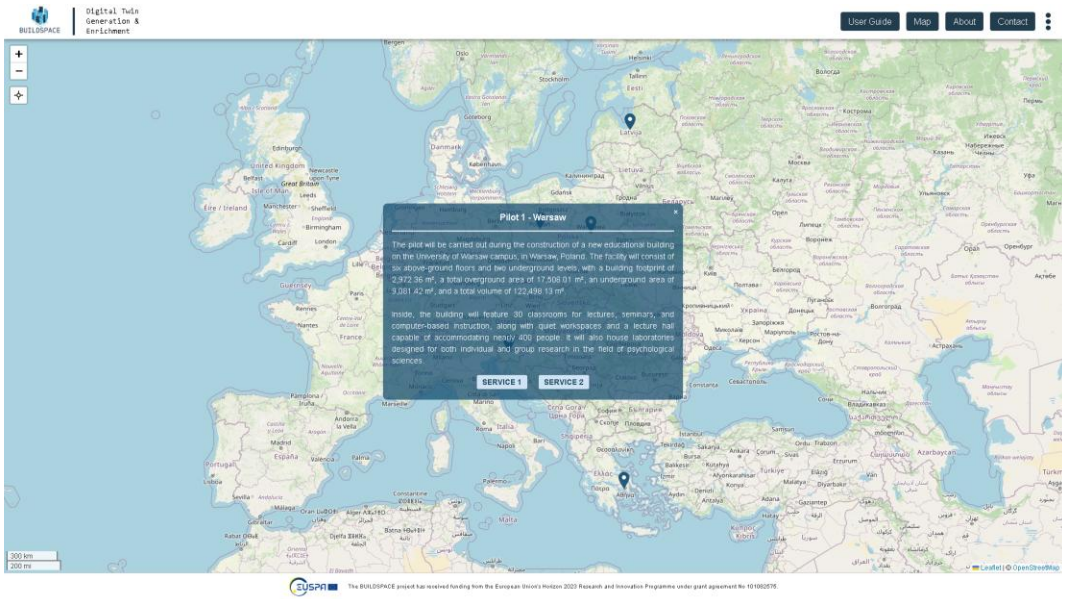


Figure 52. Pilots' information in 2D map. Access to SE1 and SE2

4.2.2.Service 2 3D viewer

SE2 is built upon geometric digital twins by integrating semantic layers, thermal imaging, and automated diagnostic tools. Through a browser-based 3D viewer powered by the integration of Potree and Cesium[12], users can explore complex models of buildings and infrastructures in a seamless and intuitive way. Potree[13] is an open-source point cloud viewer that can be hosted online and offers essential features for interactive 3D Point Clouds.

This service supports a wide range of visual and analytical functionalities tailored for diagnostics, maintenance planning, and energy efficiency assessment without the need for specialized software.

To access the 3D viewer, users need to navigate to either Warsaw or Piraeus pilot site on the interactive map and click on Service 2 in the corresponding pop-up window. The viewer will automatically load the specific point cloud model associated with that pilot site.

Once the **3D viewer** is loaded, the screen is divided into several sections (see Figure 53):

[12] Cesium is an open-source platform, that allows developers to create and visualize geospatial data in 3D within a web browser.
[13] Potree viewer: https://github.com/potree/potree/

- **Main viewport**, this is the central display area where the 3D point cloud model is rendered. Users can zoom, rotate, and pan around the model to explore building structures in full detail. Both Potree (for point clouds) and Cesium (for 3D globe) are integrated into this view.
- **Top toolbar**, providing quick access to common actions such as view resets, and measurement modes.
- **Left sidebar**, containing the project tree and all user-accessible settings grouped under different tabs.
- **Right sidebar**, containing the attribute toggles and legend, which controls how data is visualized.

Figure 53. SE2 Interface

This interface provides all necessary tools for conducting technical assessments and visual exploration of building digital twins in a single, accessible environment.

The **main viewport** is the central area of the 3D viewer where the building's 3D point cloud is displayed. It serves as the primary workspace for visual inspection and analysis. Users can navigate within this space using mouse or trackpad controls:

- **Left click and drag** to rotate the model
- **Right click and drag** to pan across the scene
- **Scroll wheel** to zoom in and out
- **Double click** on any surface to centre the view on that point

The viewport dynamically responds to changes made in the sidebars, such as activating thermal layers, toggling classifications, or isolating geometry using clipping tools. For spatial orientation, a small compass indicator appears, showing the current viewing direction relative to North.

The **top toolbar** can be seen in Figure 54.

Figure 54. Top toolbar

The **menu toggle** section controls the visibility of the **left sidebar**, which contains all core tools, settings, and model controls. By clicking the menu icon, users can **collapse or expand the sidebar** to maximize the viewing area.

The **measurement tools** section provides essential tools for geometric analysis within the 3D model (Figure 55 and Figure 56). Users can measure distances, heights, and surface areas, as well as create vertical profiles of structural elements. These tools are particularly useful for understanding spatial relationships and verifying dimensions directly within the 3D point cloud.

Figure 55. Measurements overview

Figure 56. Measurements toolbar section

Different options are allowed in the measurements' toolbar (Figure 56):

- **Point**: Select a single point to display its coordinates and attribute data.
- **Distance**: Measure the linear distance between two or more points in space.
- **Height**: Measure vertical distance between two selected points.
- **Area**: Calculate the surface area of a polygon.
- **Profile**: Create a vertical cross-section of the point cloud along a user-defined line.
- **Clear measurements**: Remove all existing measurement annotations.

The **navigation** section (Figure 57) provides advanced navigation settings that enhance the visual clarity and interactivity of the 3D viewer. Users can toggle between orbit and first-person navigation modes for optimal data interpretation.

- **Navigation modes**: Earth control, orbit control and fly mode.
- **Full extent**: Overview to locate the model.

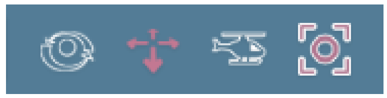


Figure 57. Navigation toolbar section

The **visualisation controls** section (Figure 58) offers quick access to standard view orientations and makes it possible to choose between perspective or orthographic camera views for optimal data interpretation. These predefined camera angles help users align the model for inspection, take consistent screenshots, or conduct precise measurements aligned with building geometry.

- **View orientations**: Top, front, back, left, and right
- **Camera projection**: Perspective or orthographic

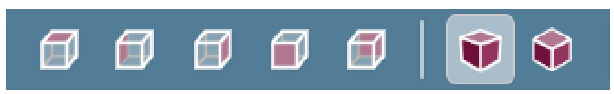


Figure 58. Visualisation controls toolbar section

The camera projection toggle allows for switching between perspective view (realistic depth) and orthographic view (parallel lines, no depth distortion nor 3D globe).

The **clipping tools** section (Figure 59) allows users to isolate specific regions of the point cloud for focused inspection. By drawing custom clipping polygons or volumetric boxes, users can hide irrelevant areas and concentrate on sections of interest. Clipping is especially helpful for analysing façades, interior spaces, or complex structures without visual distractions, optimizing data interpretation and exploration efficiency.

- **Volume clipping:** This tool allows the user to create a 3D box (clipping volume) to isolate and extract specific volumetric regions of the point cloud.
- **Polygon clipping:** This tool enables the user to draw a custom 2D polygon. The polygon defines a clipping plane that slices through the point cloud, effectively dividing it.
- **None**: No clipping action is applied.
- **Highlight**: The selected area is emphasized visually while the rest of the model remains visible.
- **Inside**: Only the content within the selection remains visible.
- **Outside**: The content inside the selection is hidden, showing only the unselected portions of the model.

Figure 59. Clipping tools toolbar section

The **left sidebar** provides access to the core analytical and visualization controls within the 3D viewer. Organised into collapsible sections, this panel enables users to interact with the 3D point cloud in a structured manner.

From adjusting rendering to accessing precise measurements, applying semantic classifications, or reviewing diagnostics, each section is purposefully designed to support specific analytical tasks making it easy to manage complex digital twin data in an intuitive and user-friendly way.

The **appearance** section enables users to control how the point cloud is visually rendered in the viewer (Figure 60). These settings affect performance, depth perception, and the user's ability to interpret spatial details in the 3D environment.

- **Point budget:** This parameter allows users to define the maximum number of points considered for display, directly influencing the visual density of the model. The default setting is 6 million points, with an upper limit of 10 million. Reducing it may improve performance.
- **Field of view:** FOV controls the camera's viewing angle from the user's perspective. The default setting of 60 degrees offers a balanced perspective suitable for most analysis tasks.
- **Speed:** This parameter adjusts the sensitivity of camera movement within the 3D environment. A higher value allows for faster navigation across large models, while lower values are preferable for fine inspection.
- **Eye dome lighting:** EDL enhances depth perception and edge visibility by simulating ambient shading between nearby points. It adds soft shadows that emphasize the geometry of the model. Users can toggle this feature on or off and fine-tune it using:
  - Radius: Controls the width of the shading effect.
  - Strength: Determines the intensity of the shading.
- **Background:** The background setting changes the colour scheme of the viewer canvas to suit different visual needs or presentation styles.

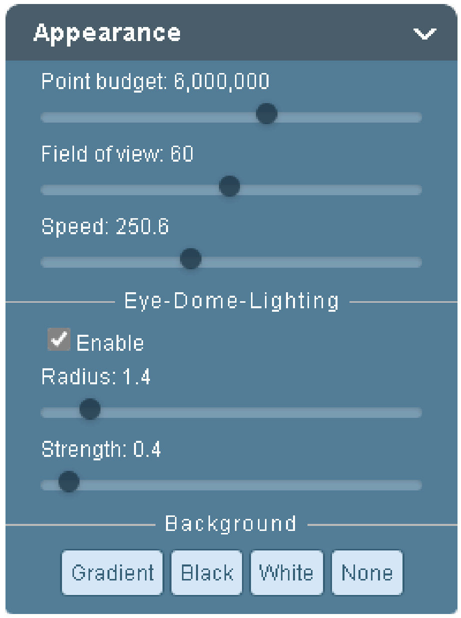


Figure 60. Appearance characteristics

The **measurements** section allows users to create, manage, and review spatial annotations directly within the 3D environment (Figure 61). Each tool provides geometric insights essential for inspection, diagnostics, and reporting.

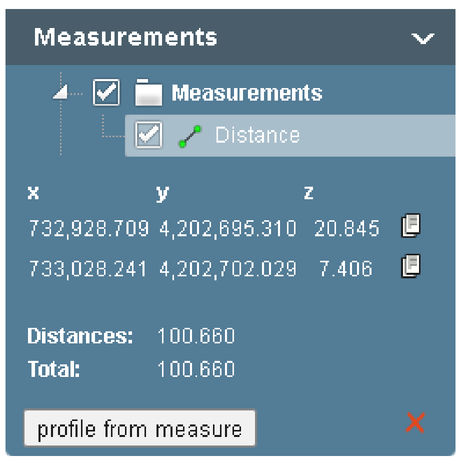


Figure 61. Measurements characteristics

All measurements created using the toolbar are listed here. By selecting one from the list, users can view its specific characteristics, such as coordinates, dimensions, or derived properties. These annotations can be toggled on/off or removed from the scene. An example of measurements section is provided in Figure 62.

- **Point, Distance, and Height:** In addition to the measurement itself, the system displays the coordinates (x, y, z) and available attribute data of each selected point. This information is valuable for cross-referencing spatial data or verifying positioning.

- **Area:** It provides the coordinates of each vertex, the calculated surface area in square meters, and, if applicable, the total enclosed volume within the defined boundary.
- **Profile:** It includes the start and end coordinates of the selected profile line, along with a 2D profile graph displaying point distribution along the section.

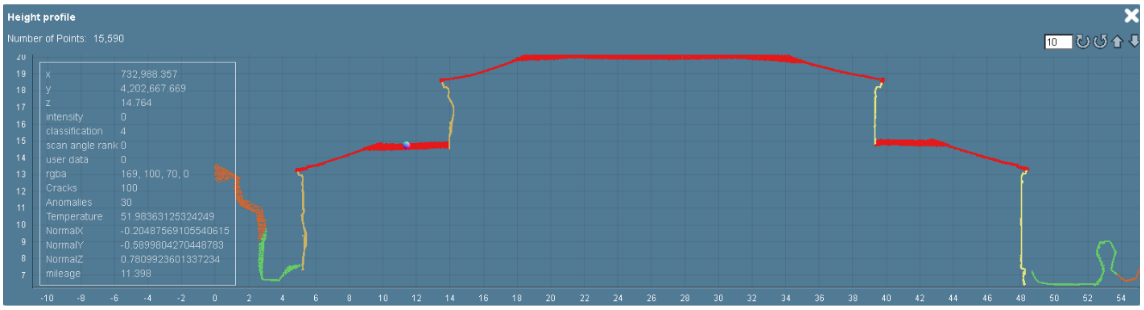


Figure 62. Section example (measurements)

The **classification** section (Figure 63) allows users to control the visibility of semantically labelled elements within the point cloud. These classifications are automatically assigned during the semantic enrichment process and represent different building components and surrounding elements.

Users can toggle between predefined filter modes to quickly adjust the visibility of model layers:

- **Interior:** Displays all elements classified as internal.
- **Exterior:** Shows only the building envelope or façade.
- **Building:** Combines both interior and exterior view.
- **Panels:** Highlights photovoltaic surfaces.

Below these, a detailed checkbox list allows for manual control of individual components. Each element is color-coded for quick identification in the 3D view.

A "Show/Hide All" option is also available to toggle all layers on or off simultaneously.

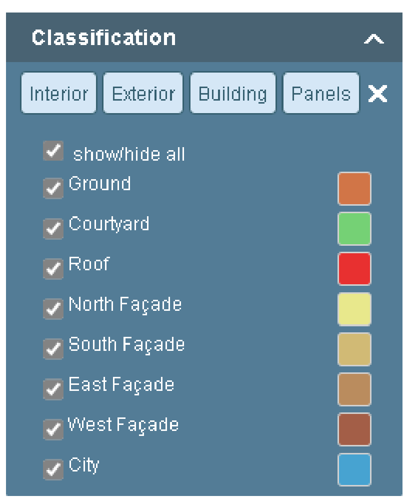


Figure 63. Classification toolbar

The **thermal anomalies** section (Figure 64) provides visual diagnostics based on thermal imaging data integrated into the point cloud. It allows users to quickly identify areas of inefficiencies across the building envelope.

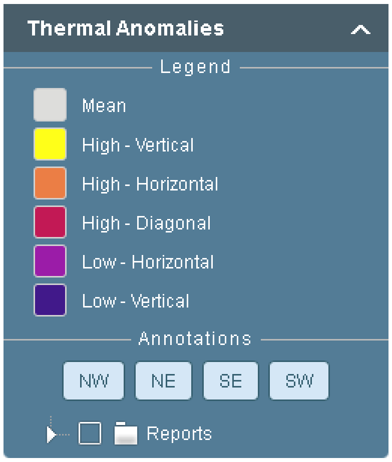


Figure 64. Thermal anomalies characteristics

A colour-coded legend helps interpret thermal conditions at a glance:

- **Mean:** Represents baseline or average surface temperatures. These areas are considered thermally "normal" and shown in grey.
- **High:** Areas with above-average temperatures. These values may be further broken down by pattern.
- **Low:** Highlights surfaces with below-average temperatures. These may also be classified by pattern.

Annotations are displayed on the model with directional labels to indicate the specific building zones where anomalies were detected. Clicking on these will toggle the visibility of all annotations assigned to that orientation, making it easier to isolate and inspect anomalies in that specific region.

Clicking on an individual annotation will automatically zoom the camera to the affected area, allowing for close inspection. Linked reports provide further insights, clustering summaries and retrofitting suggestions, as the example in Figure 65.

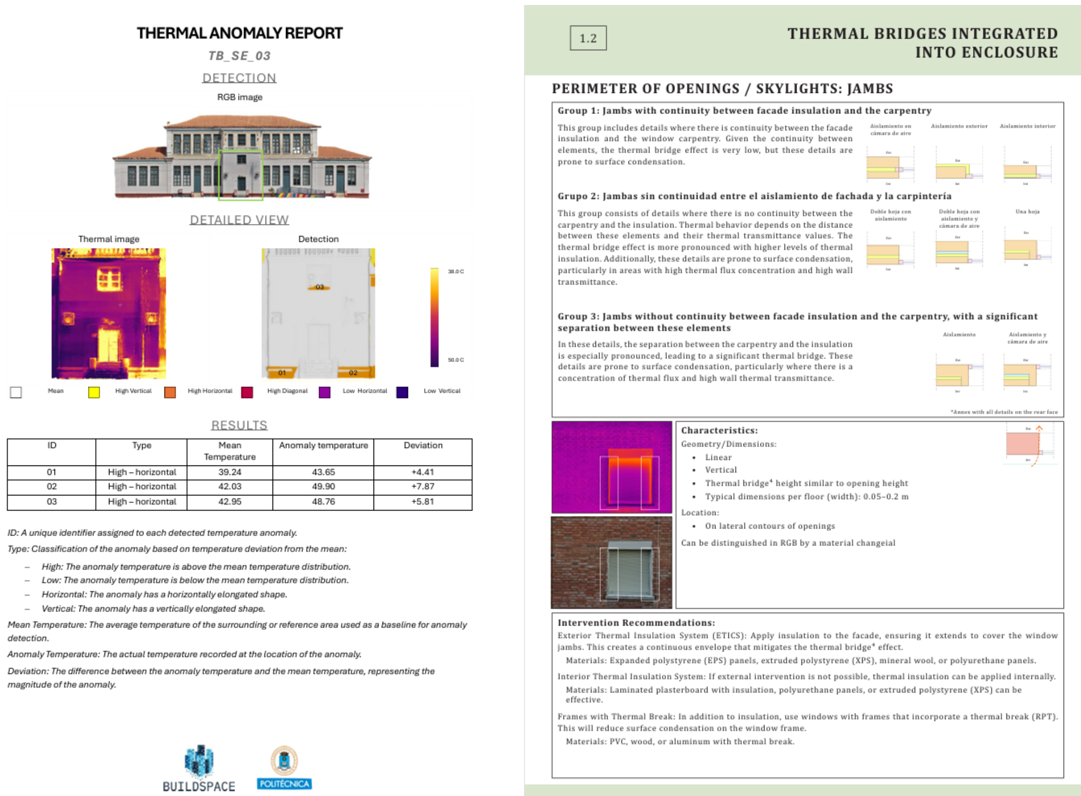


Figure 65. Report and catalogue examples

The **cracks** section (Figure 66) highlights structural pathologies detected on building façades, specifically focusing on visible surface cracks identified through semantic enrichment and image-based analysis.

Cracks are visualized as colour-coded overlays on the 3D point cloud, allowing users to quickly detect and assess areas that may require maintenance or further structural evaluation. The legend includes:

- **No Crack**: Areas without detected damage are displayed in grey.
- **Crack**: Areas where cracks have been identified are highlighted in purple.

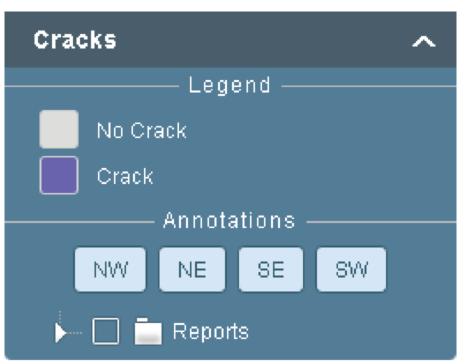


Figure 66. Cracks characteristics

As with thermal anomalies, directional annotations are used to label façade zones. Clicking on any of these labels toggles the visibility of all crack annotations for that region, making it easy to focus inspection on specific building orientations.

Clicking on an individual crack annotation zooms the viewer into the affected area for detailed examination (example in Figure 67). When available, linked reports can be accessed through icons in the panel, offering summaries that include crack location and distribution, and recommended follow-up actions.

Figure 67. Cracks annotation example

The **right sidebar** is dedicated to attribute visualization and data interpretation tools. It allows users to switch between different modes of rendering the point cloud, providing access to thematic overlays such as RGB colour, thermal data, and semantic classifications. Users can use this sidebar to tailor the visual context of the 3D model based on the type of analysis they are performing, whether identifying temperature anomalies or reviewing classification outputs.

The **RGB toggle** (Figure 68) displays the model using true-colour textures captured from photogrammetric reconstruction. This mode provides a realistic representation of the building, making it ideal for visual inspections and presentations.

Figure 68. RGB visualization

The **temperature toggle** renders the point cloud according to surface temperature values obtained through thermal imaging (Figure 69). This mode visualizes thermal behaviour across the building envelope, enabling users to detect anomalies.

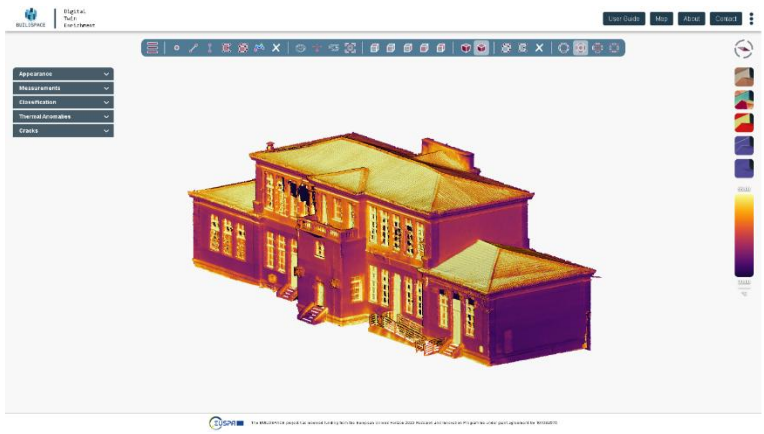


Figure 69. Thermal visualization

The **classification toggle** (Figure 70) colour-codes each point based on semantic labels automatically assigned during the enrichment process. These labels correspond to specific building elements helping users isolate and conduct targeted analysis.

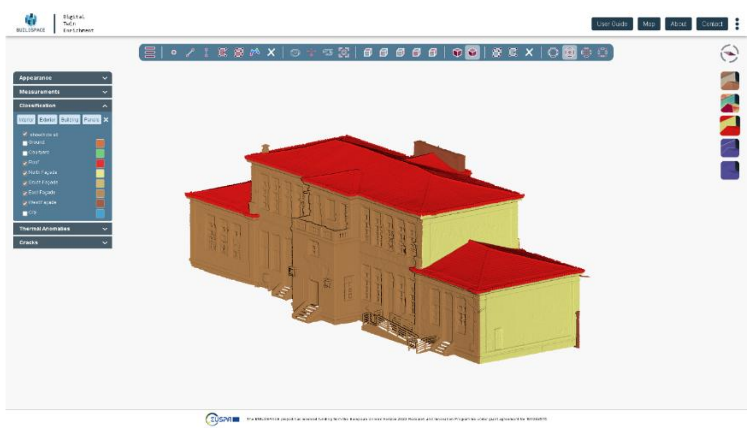


Figure 70. Classification visualization

The **thermal anomalies toggle** (Figure 71) highlights areas of the model that exhibit abnormal thermal signatures, as identified by automated processing. These are categorized relative to the mean surface temperature and further classified by pattern orientation.

Figure 71. Thermal anomalies visualization

The **cracks toggle** (Figure 72) displays detected surface cracks identified through semantic analysis and image-based enrichment. Areas labelled are visually highlighted allowing users to locate and inspect damage without manual annotation.

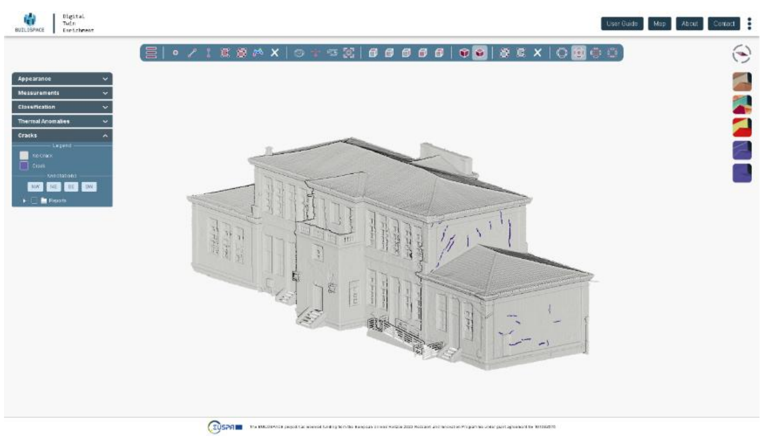


Figure 72. Cracks visualization

4.2.1.Target users and added value

SE2 is designed to support a wide range of professional users involved in building inspection, facility management, and retrofit planning, as well as non-expert stakeholders interested in the condition and energy performance of buildings. Table 14 summarises the main target user groups and the specific added value SE2 provides to each.

Table 14. Added value of the SE2 service for different user types

User type	Added value of the SE2 Digital Twin Semantic Enrichment
Public authorities and building managers (e.g., municipalities, facilities managers, heritage and maintenance teams)	• Detects structural and thermal anomalies (e.g., cracks, damp areas, thermal bridges) in building envelopes through enriched 3D point clouds. • Provides detailed diagnostics to support prioritisation of maintenance and retrofitting actions. • Enables spatial documentation of façade pathologies and solar panel issues for technical audits and renovation planning.

User type	Added value of the SE2 Digital Twin Semantic Enrichment
	• Supports compliance with energy efficiency directives by delivering detailed envelope condition data.
Researchers and consultants	• Delivers high-resolution RGB and thermal 3D data for envelope and thermographic analysis. • Supports AI-based training datasets for segmentation, defect classification, and envelope condition assessment. • Allows fusion of interior and exterior scans for comprehensive building envelope models. • Offers a calibrated and georeferenced dataset suitable for thermal simulation, digital twin alignment, and material behaviour studies
Construction and retrofitting professionals (e.g., architects, retrofit designers, energy auditors)	• Provides actionable insights to design envelope rehabilitation strategies based on detected anomalies. • Highlights thermally underperforming areas with direct access to point-level temperature values. • Enables visualisation of façade classification (floors, windows, ground, etc.) for intervention planning. • Enhances the documentation process of pre- and post-retrofit conditions.
Citizens and non-expert users	• Offers visual 3D representations of building façades combining RGB and thermal imagery. • Raises awareness about building deterioration and energy loss. • Encourages public engagement in renovation and energy transition actions through accessible and intuitive visual tools.

4.3.Adaptation to pilots

In the context of BUILDSPACE, the visualization of results plays a key role in demonstrating the potential of the services developed. While Service 1 (SE1) and Service 2 (SE2) were initially intended to operate in an integrated way, the specific technical needs of SE2 required a more flexible and tailored approach to ensure that the outputs could be properly accessed, explored and interpreted. This section outlines how the SE2 visualization solution evolved in response to these needs and how it was ultimately adapted to align with the pilot use cases.

Although the visualization component was initially under the responsibility of SE1, as stated in the Grant Agreement, compatibility issues were identified between the web viewer used by SE1 and the specific requirements of SE2. The tool did not support key functionalities needed to properly display SE2 results, such as enriched point clouds with thermal information.

As a result, the SE2 team decided to implement a dedicated web visualization solution to meet the minimum service requirements and ensure full visibility of the developed outcomes. This was an unexpected task for SE2 and had to be addressed urgently, without any direct interaction with the pilot sites, since this work was originally outside the planned scope of SE2.

To avoid the complexity and time involved in building a visualization platform from the ground up, which would have required years of development, the team opted to adapt Potree.

Three versions of this viewer were progressively developed:

- The **first version** provided a basic structure to host the pilot results but presented usability limitations and technical issues with certain tools.
- The **second version** focused on improving user accessibility, introducing interface elements to make navigation faster and more intuitive.
- The **third and latest version** integrated the feedback collected in Deliverable D4.3. This version was designed to be usable by both experts in the field and non-specialized users, with particular attention to accessibility, clarity, and ease of use.

Since BUILDSPACE initially conceived Services 1 and 2 as integrated and interoperable, but this integration was not ultimately possible, SE2 has also developed a joint landing page. This entry point features a 2D map that allows users to view the locations of all pilots and access the corresponding visualization platforms of each service separately. This solution facilitates navigation across the different outputs of the project and offers a unified access point despite the technical separation of the services.

4.4.Technical developments – Final version

The final release of the SE2 service consolidated its technical components and introduced several significant advancements beyond the previous development phase. While earlier versions focused on RGB and thermal data integration, the final release completed the full analytical workflow, including advanced detection features, automated reporting, and an interactive 3D visualization platform.

Major final developments included:

- **Generation of multiscale point clouds** enriched with RGB, thermal, and classification data, accurately georeferenced using control points provided by pilot partners. RGB meshes were discarded in the final version to ensure platform performance and avoid redundant information.
- **Thermal anomaly detection** in both pilots, applying statistical outlier analysis on point cloud temperatures and classifying anomalies as vertical or horizontal using PCA-based geometric descriptors.
- **Crack detection** in the Greek pilot, through a refined YOLO-based pipeline trained with augmented image datasets. Detected cracks were projected onto the 3D model and filtered by confidence thresholds and construction context.
- **Solar panel anomaly detection** in the Polish pilot, using statistical analysis workflows to identify malfunctions. Results were spatially localized and linked to report generation modules.
- **Automated generation reports** for each type of anomaly (thermal anomalies, cracks, and solar panels). Reports include location, severity, visibility in RGB or thermal data, and tailored remediation suggestions, supporting expert and non-expert interpretation.

- **Deployment of an interactive 3D web platform**, allowing users to explore each pilot's outputs with multiple tools (navigation, data filtering, anomaly highlighting, report access). A 2D landing page was also created to centralize access and enable selection of individual pilots and services.

This final version ensures the SE2 service is fully aligned with BUILDSPACE goals, offering high-quality results, automation, and user-oriented visualization in both pilot contexts.

The final SE2 service is accessible through the BUILDSPACE platform at https://se2-buildspace.euinno.eu/

4.5.Replication and uptake potential

The SE2 has been developed with modularity and cross-context adaptability in mind, allowing for its deployment in various building types and urban settings. By leveraging UAV-acquired thermal and RGB imagery and advanced AI-supported diagnostics, SE2 provides a scalable method for assessing building envelopes, detecting thermal anomalies, and enhancing digital twin models through enriched 3D visualization and reporting. This makes it a valuable service for both new constructions and existing buildings undergoing renovation planning or quality verification.

Several aspects enhance SE2's replication potential across cities and regions:

- **Modular architecture and sensor flexibility**: SE2 can incorporate UAV flights, SLAM techniques, and handheld sensors, adapting to different spatial constraints and data availability. This allows it to serve both high-rise urban areas and low-density building environments.
- **Scalable methodology**: The system processes RGB and thermal imagery, along with point cloud data, to identify anomalies. Detection algorithms are supported by AI, which enhances replicability through automated workflows.
- **Generic applicability**: SE2 has been successfully piloted in contrasting contexts, an existing school in Greece and a newly built university in Poland, demonstrating its flexibility in supporting both quality control in new buildings and diagnosis in older ones.
- **Potential for automation**: Future developments aim to integrate UAV flight planning and autonomous inspection routines, enabling city-scale deployments with minimal manual intervention.

Insights gathered from the pilot deployments further inform the replicability strategy:

- In Greece, feedback highlighted the value of capturing thermal envelope conditions for prioritising retrofits, especially in buildings with limited technical documentation.
- In Poland, SE2 supported quality assurance in a newly built structure, confirming its utility in verifying construction outcomes against design specifications.
- Stakeholders valued the ability to visually compare design models (BIM) with real-world scans and to detect thermal anomalies early, avoiding costly post-construction corrections.
- During co-creation workshops, participants emphasised the importance of intuitive web interfaces and fast access to 3D and thermal data.
- Suggestions included clearer colour-scale calibration for thermal maps and enhanced date-selection features for multi-temporal comparisons.

Early validation and user feedback confirmed several strengths of SE2:

- Its ability to deliver enriched digital twins based on thermal and geometric data was seen as particularly useful for public authorities managing large building stocks.
- The automated detection of cracks and thermal anomalies reduced subjectivity and manual effort in building inspection processes.
- Stakeholders highlighted the added value of integrating anomaly detection into maintenance workflows and the potential for city-wide rollout to support renovation strategies.

Altogether, SE2 demonstrates strong replication and uptake potential by combining technical versatility, multi-scale applicability, and user-driven refinement. As European cities strive to meet energy efficiency and resilience targets, SE2 offers a practical, adaptable, and impactful solution.

5. BUILDSPACE service SE3 – Built Environment Climate Scenarios (city scale)

The Built Environment Climate Scenarios (SE3) service offers an interactive, map-based environment for analysing how heating, cooling and domestic hot water (DHW) energy demands of residential buildings evolve under current and future climate conditions. It integrates geospatial data, simplified energy balance models and future climate scenarios to support planning decisions at city, district and building levels.

In addition to estimating energy demand under multiple Shared Socioeconomic Pathways (SSPs), the service includes functionalities for simulating passive retrofitting strategies and assessing rooftop PV generation potential. The outputs are visualised using colour-coded layers based on national Energy Performance Certificate (EPC) schemes, enabling intuitive comparisons and analyses.

The service is structured around a user-friendly interface that allows dynamic scenario switching, spatial filtering, and building-level inspection. All data and results are accessible through standard web browsers, with no need for external software. Its design facilitates evidence-based planning for energy efficiency improvements, investment prioritisation, and climate resilience strategies.

5.1.Input and output

The SE3 service combines multiple data sources to generate outputs that support energy planning at building and city scale. The following section outlines the key input components and resulting outputs.

Input data:

- **Building and urban data.** The geometric and descriptive characteristics of buildings are obtained from cadastral sources or OpenStreetMap (OSM), developing on data availability in the pilot cities. These datasets include building footprints, number of floors, height and gross surface area. When height data are unavailable, digital terrain and surface models (DTM/DSM) are used to derive elevation profiles. An automated process also detects party walls, improving the accuracy of thermal boundary assumptions by identifying shared surfaces that reduce heat loss. This geometric base is crucial for estimating surface-area-dependent energy flows and for associating buildings with typological information.
- **Building typology and envelope characteristics.** Each building is assigned to a typology using the TABULA/EPISCOPE[14] database. This allows the definition of thermal properties such as U-values (transmittance) for walls, roofs and windows based on construction year and building type. Additional assumptions, such as ventilation rates, internal gains and standard occupancy, are applied consistently, following Energy Performance of Buildings Directive (EPBD) [15] recommendations. This typological standardisation allows consistent energy demand simulation even in data-scarce environments.

[14] TABULA/EPISCOPE Project: https://episcope.eu/, TABULA Web Tool: https://webtool.building-typology.eu/
[15] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401275&pk_keyword=Energy&pk_content=Directive

- **Climate data**. The service incorporates both current and future climate conditions. Present-day data are based on Typical Meteorological Years (TMYs), while future projections are derived from CMIP6 climate models under three Shared Socioeconomic Pathways (SSP245, SSP370, SSP585), which represent moderate to extreme emissions scenarios. They come from Copernicus Climate Change service (C3S)[16]. These datasets are bias-corrected through Quantile Mapping using 30-year records from local weather stations and converted into hourly profiles based on PVGIS[17] patterns. Time horizons for projections include 2030, 2040 and 2050, enabling comparison across scenarios and timelines. Solar irradiation data from the PVGIS service are used both to estimate internal solar gains (as part of the HDD/CDD-based thermal model) and, separately, to assess rooftop PV generation potential.
- **Solar photovoltaic potential data.** Rooftop potential is modelled using PVGIS data, with corrections for roof slope and orientation. Steeply sloped or north-facing surfaces are excluded from potential installation zones. Energy generation is calculated using specifications of Tier-1 PV modules (e.g., Jinko Solar[18]), assuming a typical system loss of 20% and installation costs around 960 €/kWp. This enables city-scale mapping of annual energy yields from PV systems and supports analysis of renewable integration.
- **Retrofitting strategy definitions.** A catalogue of passive renovation measures is included in the service, covering envelope upgrades such as façade insulation, roof insulation, and window replacement. Each measure includes its U-value and estimated implementation cost per square metre. Users can apply one or more measures to simulate their impact on energy demand, allowing a cost-benefit comparison under current and future climate conditions. These scenarios directly affect the building's thermal properties in the model, updating its estimated performance.

The overall structure of input integration, scenario modelling and interactive functionalities are summarised in Figure 73.

[16] https://climate.copernicus.eu/
[17] PVGIS (Photovoltaic Geographic Information System): https://re.jrc.ec.europa.eu/pvg_tools/es/
[18] https://www.jinkosolar.com/en/

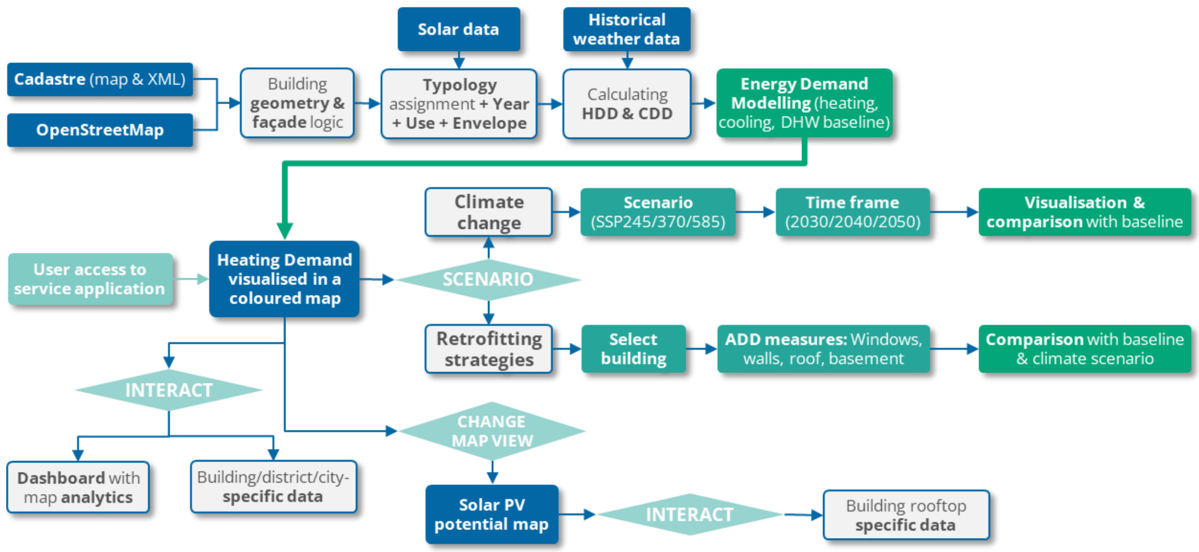


Figure 73. Workflow of SE3: data processing, scenario modelling and user interaction outputs

Outputs:

- **Energy demand maps.** The service produces spatially detailed energy demand estimates for heating, cooling and domestic hot water (DHW), expressed in kWh/m² per year. Results for heating are displayed as colour-coded maps using national Energy Performance Certificate (EPC) schemes (e.g., Latvian EPC in Riga), allowing quick identification of poorly performing buildings and neighbourhoods. These maps are recalculated dynamically depending on the selected climate scenario and timeframe.
- **Building-level analytics.** Users can click on any building to access a detailed panel presenting construction year, typology, geometry (e.g., façade and window area), compactness and volume above ground. It also shows energy demand estimates, broken down by heating, cooling and DHW. This view supports detailed analysis at the individual building level, including before-and-after comparisons for retrofitting strategies.
- **Scenario explorer and comparison mode.** Users can toggle between different emissions pathways (SSP245/370/585) and projection years (2030–2050), as well as compare baseline and future performance or pre- and post-retrofit states. This functionality helps visualise the effect of both climate change and intervention strategies on the energy performance of the building stock.
- **Aggregated statistics and data panels.** A bottom panel dynamically summarises all buildings currently visible in the map viewport or within a selected district. Metrics include the number of buildings, average heating demand, and distribution of buildings by EPC class and construction period. This provides a quick overview of building stock performance at different spatial scales. Filters can be applied in this panel.
- **Retrofitting simulation results.** When a user selects renovation measures, the service updates the building's thermal properties and recalculates its energy demand. The results include the new EPC classification, estimated annual energy savings, and implementation cost. Users can assess individual and combined measures and compare outcomes across different climate scenarios.

- **Solar PV potential maps.** Standalone map displays the estimated maximum annual rooftop PV generation potential per building. This feature allows exploratory analysis of solar opportunities. When a building is selected, the left data panel presents detailed information, including rooftop area, suitable installation area, nominal solar radiation, estimated PV output, number of panels, peak capacity (kWp) and an approximate investment cost.

Together, these outputs provide a robust basis for comparing energy performance across timeframes and interventions, helping cities prioritise actions aligned with climate adaptation goals.

5.2.User experience

SE3 is accessed through an intuitive web interface designed around a city-scale map, where individual buildings are visualised as colour-coded polygons based on their estimated heating energy demand. The colour scale is aligned with national Energy Performance Certificate (EPC) classes, suing the Latvian EPC scheme for the Riga pilot. This layout provides users with an immediate visual impression of building-level performance and spatial trends across districts and neighbourhoods.

Users interact with the tool via a streamlined navigation flow that guides them through various stages of analysis. The interface supports multiple modes of operation, including baseline and future energy demand exploration, retrofitting scenario simulation, and solar PV potential viewing. The following subsections describe the key functionalities and navigation structure from the user's perspective.

5.2.1.Interface and navigation workflow

Upon logging into the SE3 interface, users are presented with a city map displaying the current heating demand of the residential building stock. Navigation and interaction are supported through four core workflows in subsequent sections: energy demand exploration, scenario simulation, retrofitting strategies simulation and solar PV potential visualisation.

5.2.1.1.Energy demand exploration

The default view presents heating energy demand under baseline climate conditions, visualised on a city-scale map with buildings colour-coded according to their energy performance. The EPC-based view, aligned with the Latvian classification used in the Riga pilot, provides immediate insight into spatial trends across districts and individual buildings (see Figure 74).

Users can interact with the map to:

- **Zoom in/out and pan** across the city to explore both district-wide energy patterns and individual building performance. This supports both large-scale planning and building-specific analysis.
- **Click on a building** to access detailed information panel (Figure 75), showing attributes such as construction year, typology, façade and window surface area, and calculated energy demands for heating, cooling, and DHW.

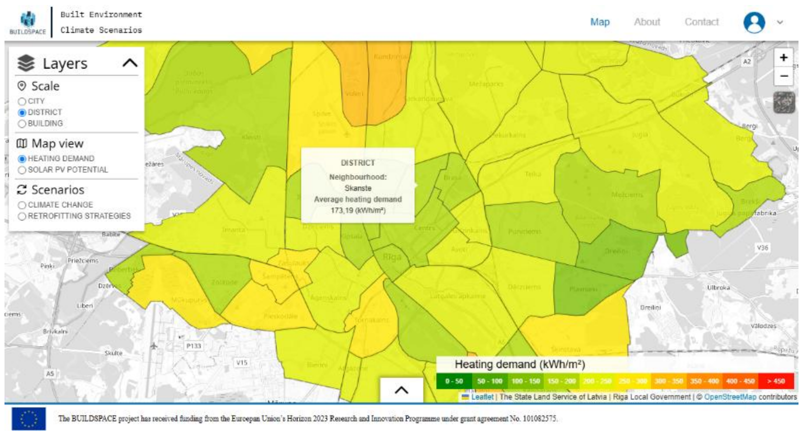


Figure 74. SE3 District-scale view showing average heating energy demand using EPC-based colour coding

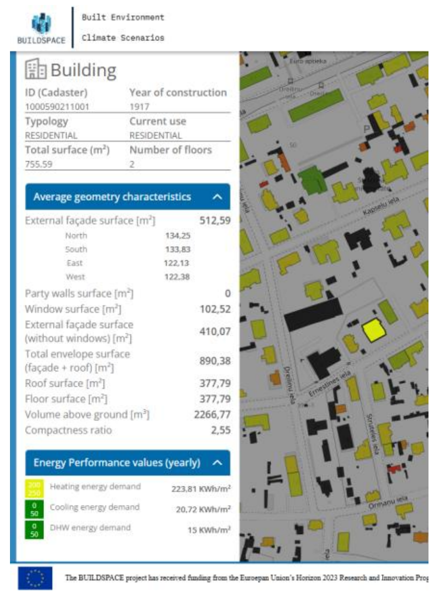


Figure 75. SE3 Building-level information panel displaying geometric attributes and energy performance values

- **Use the bottom data panel** to view aggregated statistics for all buildings currently visible in the screen (Figure 76). This includes metrics like the number of buildings, average heating demand, and distributions by EPC class and construction year. Users can also **filter buildings** displayed on the screen based on demand class or year of construction to refine their analysis simply clicking in the graphs of this panel (Figure 77).

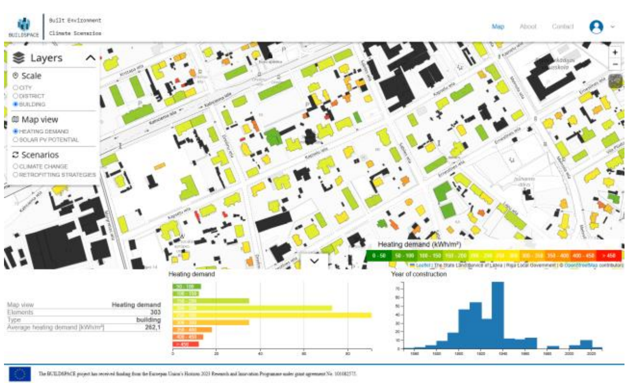


Figure 76. SE3 Bottom panel with aggregated heating demand statistics for selected buildings

Figure 77. SE3 View of filtered buildings based on EPC class

5.2.1.2.Scenario simulation

The climate scenario feature allows users to switch between the three Shared Socioeconomic Pathways (SSP245, SSP370, SSP585) and select future timeframes (2030, 2040, 2050). When a scenario is applied, heating and cooling demand estimates are recalculated and displayed using the same EPC-based colour scale, allowing direct comparison with the baseline (see Figure 78), including the additional information building panel at the left side, which compares the energy performance values (Figure 79).

Figure 78. SE3 Split-screen visualisation comparing baseline and SSP370 scenario at 2040 for heating demand

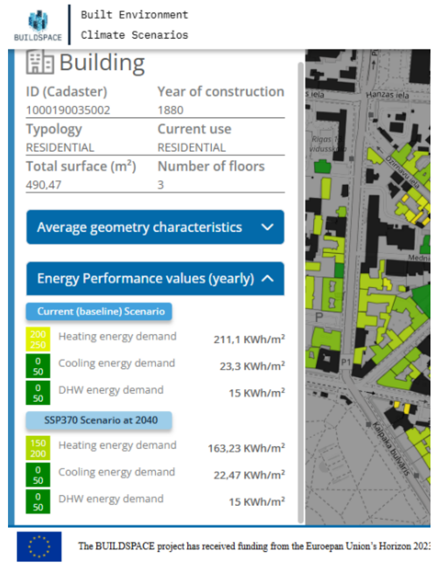


Figure 79. SE3 Building-level comparison of current vs. future energy demand under climate scenario SSP370

5.2.1.3.Retrofitting strategy simulation

Users can select a specific building and simulate the application of passive renovation measures, such as upgrading windows, roof or façade insulation (see Figure 80). Once a scenario is defined, the tool updates the building's U-values and recalculates the energy demand and EPC label. Results include both absolute and relative energy savings and the associated implementation cost as can be seen in Figure 81. Users can toggle between pre- and post-retrofit views, and also compare results across future climate scenarios (see Figure 82 and Figure 83).

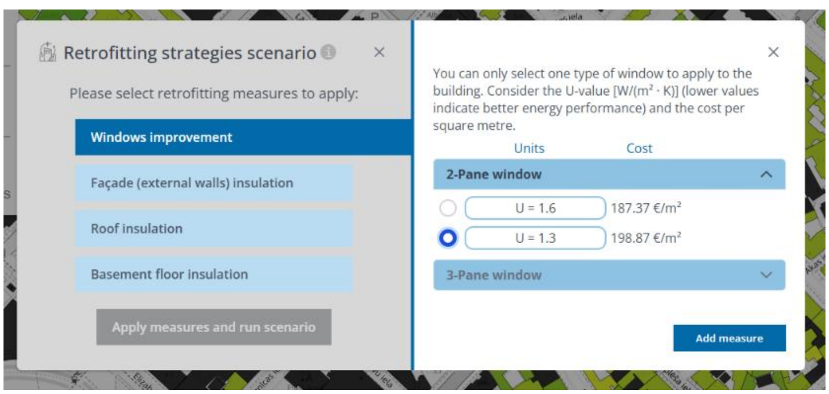


Figure 80. SE3 Retrofitting simulation configuration showing window upgrade options

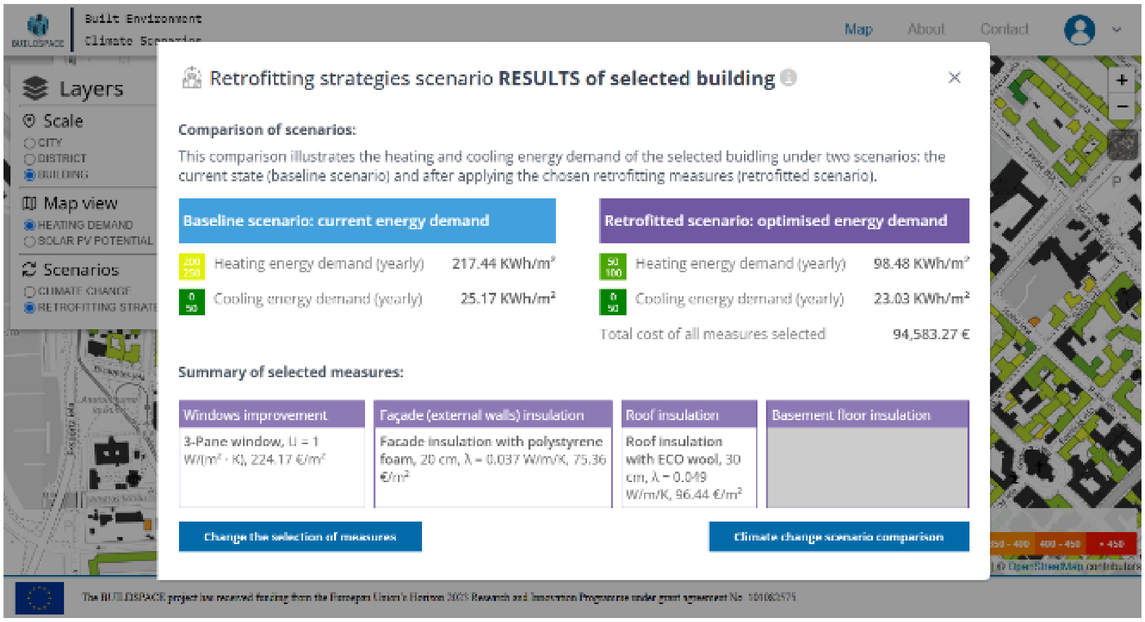


Figure 81. SE3 Retrofitting simulation results panel showing performance improvement and cost of selected measures

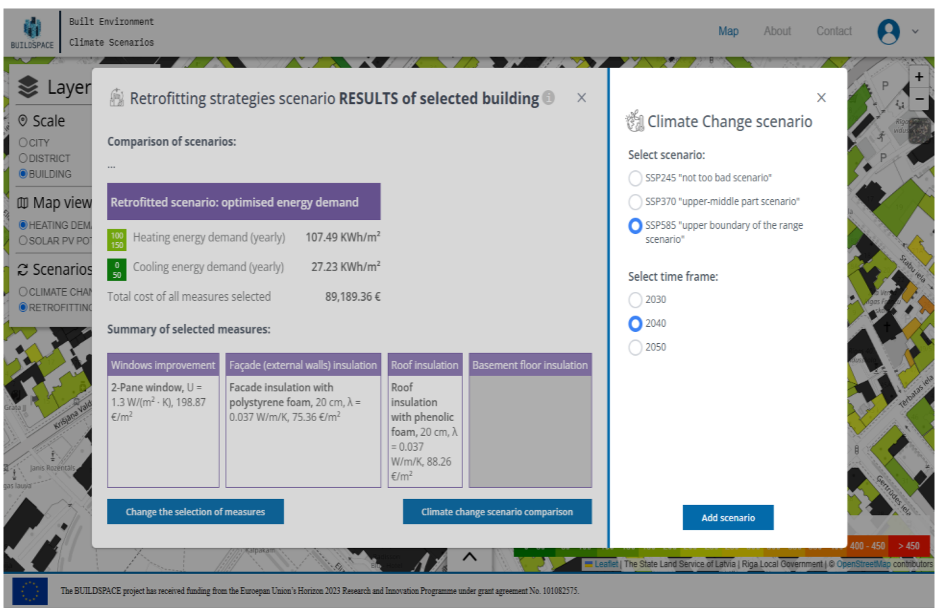


Figure 82. SE3 Scenario selection panel for evaluating retrofitting performance under future climate conditions

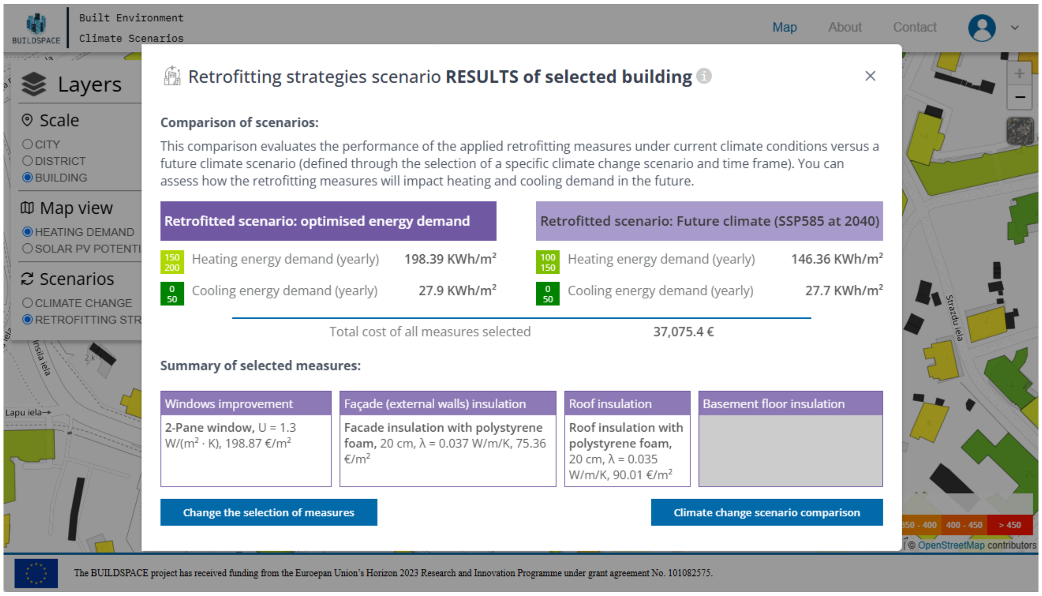


Figure 83. SE3 Retrofitting simulation results panel showing the comparative performance of selected measures in baseline scenario and under selected future climate scenario

5.2.1.4. Solar PV potential visualisation

A dedicated map view displays rooftop solar PV potential for each building (available in Riga), as shown in Figure 84. By selecting a building, users can view estimated solar irradiation, suitable installation area, peak system capacity, expected energy output, and an approximate investment cost (see Figure 85).

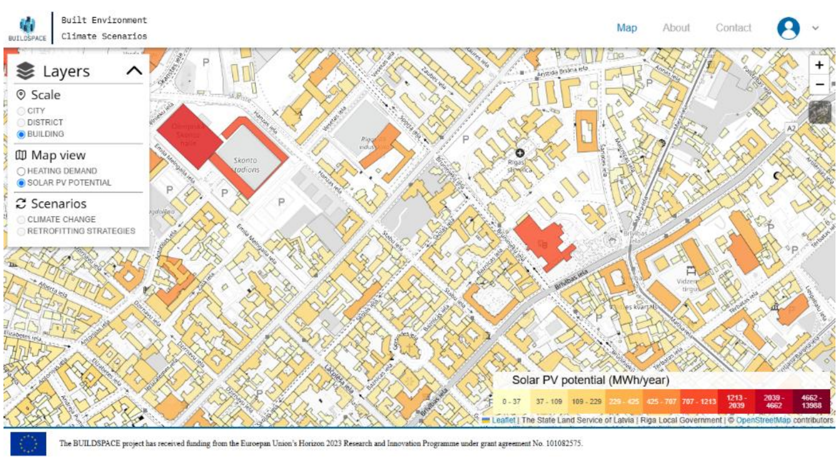


Figure 84. SE3 Map view of rooftop solar PV potential

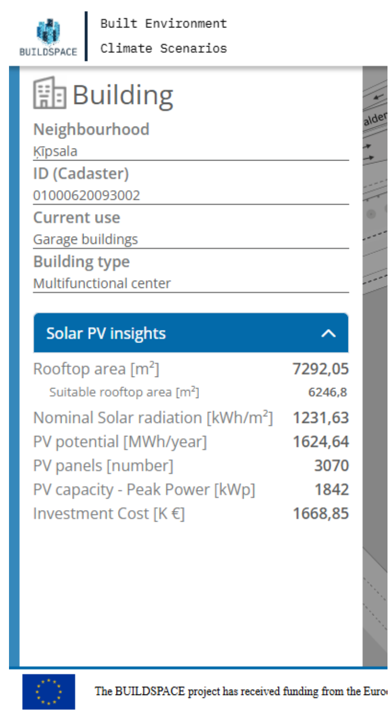


Figure 85. SE3 Building-level information panel with insights of PV potential

5.2.2.Target users and added value

The SE3 is designed to support a range of professional users, as well as broader stakeholders involved in urban energy planning. Table 15 summarises key user groups and the added value of the service for them.

Table 15. Added value of the SE3 service for different user types

User type	Added value of the SE3 Built Environment Climate Scenarios
Public authorities and planning agencies (municipal energy teams, urban planners, policy-makers)	- Identifies energy-inefficient buildings and districts using EPC-based mapping and statistics. - Simulates the impact of climate change on heating and cooling demand using CMIP6 scenarios (SSP245/370/585). - Evaluates retrofitting strategies with cost-benefit results and future scenario resilience. - Provides solar PV potential insights to support rooftop energy planning. - Facilitates evidence-based policy development and prioritisation of investments aligned with climate neutrality goals.
Researchers and consultants	- Offers a validated methodology combining building typologies, steady-state energy modelling, and localised climate projections. - Enables in-depth analysis of climate adaptation and mitigation scenarios at building and city scale. - Supports benchmarking, model calibration, and integration into broader urban energy system assessments.
Citizens and non-expert users	- Provides a simple, visual interface to explore building energy performance in their neighbourhood. - Displays future energy demand trends and solar PV suitability at the building level. - Enhances public awareness and engagement in building renovation and sustainability initiatives.

5.3.Adaptation to pilots

The SE3 was adapted to the specific needs of the Riga pilot through close collaboration with municipal stakeholders, who provided feedback on data requirements, usability preferences, and visualisation expectations. The service was configured using local weather historical data, besides Copernicus climate data, the Latvian EPC classification scheme, and building information derived from cadastral records.

During development, pilot-specific customisations were implemented to enhance the relevance and accuracy of the tool. For example, minimum thresholds were adjusted to exclude small non-heated buildings (e.g., garages or warehouses), after stakeholders indicated that their inclusion distorted aggregate heating demand statistics. Additionally, concerns regarding the overestimation of heating demand led to a data exchange: Riga city provided EPC records and SECAP-derived demand estimates to support the calibration and validation of the modelling approach.

Feedback also influenced the treatment of building geometries. Stakeholders pointed out inconsistencies between visualised shapes and official cadastral maps. These were traced back to differences in how party walls and shared boundaries are represented. In response, the team explored an alternative version using solely cadastral data, applying a statistical estimation of shared wall ratios to improve accuracy while maintaining correct thermal boundary assumptions.

Further refinements included:

- Adapting the format of the numbers to the Latvian national convention, which is different from UK standard (e.g., spaces for thousands, commas for decimals).
- Improving transparency on modelling assumptions by expanding the explanatory content in the "About" section and adding information pop-ups. These include clarifications on window-to-wall ratios, party wall definitions, and surface calculation methods.

Preliminary pilot feedback also confirmed the added value of SE3's key features, particularly the EPC-based mapping, scenario toggling, and the ability to isolate specific building cohorts (e.g., pre-1940 stock). This helped validate both the technical direction and the interface design. Additional structured user feedback and validation metrics will be reported in the corresponding WP4 deliverables

5.4.Technical developments – Final version

The final release of the SE3 service consolidated its functionalities and introduced several key advancements beyond the second release. While the dynamic climate scenario explorer and interactive visualisation modes were already developed earlier, the final version focused on expanding analytical capabilities and integrating additional features that enhance strategic planning.

Major final developments included:

- **Full integration of the solar PV potential map**, visualising the annual rooftop photovoltaic energy yield (kWh/m²) at the building level. This layer was incorporated into the main map interface with consistent visual logic and interactivity, enabling combined analysis with energy demand data.
- **Development of the retrofitting modelling module**, which allows users to apply predefined renovation strategies to selected buildings or filtered cohorts. Energy demand values are recalculated in real time to illustrate the impact of specific interventions (e.g., insulation upgrades, window replacement), supporting cost-benefit analysis and prioritisation.
- **Final calibration and localisation improvements**, including adjustments to energy demand thresholds, formatting of numerical values (e.g., Latvian number formats), and visual refinements based on pilot feedback.

The final SE3 service is accessible through the BUILDSPACE platform at **https://tools.cartif.es/built-climate-scenarios/**, with the following credentials:

- Username: buildspace-se3@cartif.es
- Password: builDSpaceSE3_2024

5.5.Replication and uptake potential

The SE3 service has been designed with a modular and data-flexible architecture to facilitate replication in a wide range of urban contexts. Its core methodology, based on typological classification, steady-state energy modelling, and climate scenario simulation, ensures compatibility with both data-rich and data-scarce environments. This makes SE3 a valuable tool for cities at different stages of digitalisation or with varying access to building-level datasets.

Several features enhance the **replicability of SE3** across European cities and beyond:

- **Data flexibility**: The tool supports integration of both cadastral data and OpenStreetMap (OSM) inputs. While national cadastral sources are preferred when available, OSM provides a viable alternative for initial deployments or smaller-scale implementations.
- **Generic methodology**: Building energy demand is calculated using standardised archetypes from TABULA/EPISCOPE, enabling straightforward typology matching for most EU contexts. Climate data inputs are based on widely accepted CMIP6 scenarios and the PVGIS solar database.
- **Modularity and scalability**: The system architecture is modular, with independent components for energy demand modelling, retrofitting simulation, and solar PV potential estimation. This allows progressive deployment — from a basic EPC mapping tool to a fully integrated renovation and climate scenario platform — and supports scalability from district to city-wide applications.
- **Web-based interface**: As a browser-accessible service, SE3 can be used without the need for local software installation, facilitating cross-departmental and multi-stakeholder access in different municipal settings.

These characteristics position SE3 as a high-potential solution for cities engaging in building stock decarbonisation, particularly those participating in EU-level initiatives such as SECAP, Climate City Contracts, or Mission Cities.

Additionally, the **pilot in Riga** provided **practical insights fro improving the service's accuracy and usability.** Feedback from local stakeholders led to refinements such as excluding non-heated small structures (e.g., garages) to improve statistical reliability, enhancing alignment of building geometries with cadastral records, and improving transparency through expanded explanatory content and localized number formatting. These adjustments aimed to improve trust in the visual outputs and ensure usability in the local context. City-provided EPC records and SECAP-derived data were also used to calibrate and benchmark energy demand estimations.

These experiences confirmed that while SE3 offers a strong technical foundation for replication, **customisation to local conventions, data structures, and user needs is key to adoption**.

While formal validation results will be reported under WP4, qualitative **feedback gathered** during pilot workshops and testing sessions confirmed several **strengths**:

- Users appreciated the **intuitive interface and layered visualisation**, particularly the EPC-coloured mapping and real-time comparison of baseline vs. future scenarios or retrofit impacts.
- The tool was considered **well-suited for supporting renovation planning**, thanks to its ability to simulate and visualise energy savings across multiple intervention types.

- Pilot stakeholders recognised the added value of incorporating **climate change projections and PV potential**, which helped contextualise energy performance under long-term sustainability goals.

The positive reception and adaptability demonstrated during the pilot underscore SE3's potential for uptake by other cities seeking to visualise and accelerate the decarbonisation of their building stock.

An **early replication of the SE3 service was carried out in the city of Piraeus (Pilot 3)** to support the development of SE4 (Urban Heat Analysis and Resilience), as detailed in **section 6.5**. Specifically, SE's modelling of cooling energy demand under future climate scenarios was integrated into SE4 to provide a more comprehensive assessment of urban heat risk and building energy performance. This cross-service application demonstrates the flexibility and interoperability of service's methodology, as well as its potential to act as a foundational component for other resilience-oriented tools. Further insights into this replication effort, including challenges related to data quality and the actions taken to enhance local datasets (e.g., Mapathon), are provided in the SE4 **section 6.5**.

6. BUILDSPACE service SE4 – Urban Heat Analysis and Resilience (city scale)

The Urban Heat Analysis and Resilience (SE4) service addresses the increasing concern over urban heat and its social and environmental impacts. It is designed to assess urban heat risk at high spatial resolution by combining heat exposure data with demographic and socio-economic indicators. This enables the evaluation of social vulnerability to heat, highlighting which sections of the urban population are at greatest risk due to factors such as economic status, education levels, households' composition, etc. The service also focuses on urban microclimatic phenomena, assessing the impact on the energy performance of buildings and supporting climate adaptation and mitigation strategies for urban stakeholders.

The service is designed with replicability across European cities in mind, using open data sources and flexible methodologies to ensure broad applicability.

6.1. Input and output

The **inputs** required for the Urban Heat Analysis and Resilience service include:

- Statistical georeferenced socio-economic and demographic data to assess vulnerability at district level.
- Data from citizen weather stations to assess the urban heat distribution and intensity within the city.
- Buildings' geometry (boundary and area, façade and party walls area), year of construction, height, buildings' use and/or typology and other building characteristics provided by the pilot and complemented with OpenStreetMap database.
- **Datasets obtained from Copernicus services:**
    - Satellite-derived geospatial data, Normalized Difference Vegetation Index (NDVI), and high-resolution RGB bands for land use and urban surface mapping.
    - Digital Elevation Model (DEM) that represents the surface of the Earth including buildings, infrastructure and vegetation.
    - CORINE Land Cover for the classification of land into different land-use categories such as urban areas, forests, agricultural areas and wetlands.
    - ERA5 global climate reanalysis data

The **outputs** generated by the service include:

- **Urban Climate Zones (UCZ) map** – These zones are created by grouping areas with similar thermal conditions. The goal is to identify climatically homogeneous urban zones to support planning and adaptation.
- **Urban Heat Risk (UHR) map** – A high-resolution georeferenced map displaying areas of Urban Heat Risk, combining urban heat hazard, exposure, and vulnerability. This map helps identify priority areas for intervention.
- **Urban heat hazard map** – A high-resolution georeferenced map with the distribution of the urban heat and its intensity.

- **Urban Heat Vulnerability (UHV) map** – Displays socio-economic and demographic vulnerability to heat, considering the ability of communities to adapt to high temperatures.
- **Urban Heat Exposure (UHE) map** – Represents the areas most exposed to high temperatures, considering the most populated areas.
- **Buildings' energy demand**: Estimation and visualisation of the energy demand of the city buildings' stock. This map has been included for each of the future climate scenarios using weather files generated during the project.
- **Decision support tool**: A selection of solutions for mitigation and adaptation to urban heat and identification of potential areas for intervention per solution.
- **Creation of long temporal series** of temperature and relative humidity for each one of the UCZ detected to improve the urban assessment (e.g., weather files for the evaluation of energy performance of buildings). These are available for the current and future climate scenarios.

The service allows users to interact with the maps, select different climate scenarios, and focus on specific areas of interest. These outputs are crucial for evaluating the resilience to heat, the impact of urban heat on energy demand and for guiding targeted adaptation and mitigation efforts.

6.1.1.Consideration of the gender-related vulnerability

In the vulnerability assessment, particular attention was paid to integrating a gender-sensitive perspective, recognising that urban heat does not affect all demographic groups equally[19]. The following indicators were included to reflect differentiated vulnerability among women:

- **Percentage of households with single women over 65 years old**: Often more susceptible to heat-related health impacts and living alone may limit social support or assistance during heat events, while social inequalities accumulated over the lifetime (such as lower pensions and limited access to resources) further exacerbate their exposure and reduce adaptive capacity.
- **Percentage of women as breadwinners**: Capturing socioeconomic vulnerability linked to household dependency and labour market inequalities.
- **Women as single parents**: Acknowledging the combined effect of caregiving responsibilities, potential isolation, and economic strain in coping with extreme temperatures.

These indicators were incorporated to ensure a more inclusive and equitable understanding of urban heat vulnerability, supporting the development of targeted resilience strategies.

6.2.User experience

The user experience of the SE4 has been carefully designed to ensure clarity, accessibility, and practical value for a wide range of stakeholders. The platform provides an intuitive interface that enables users to explore urban heat-related risks across Piraeus's census tracts. The interface has been developed to offer a user-friendly and visually engaging experience. It features interactive maps with multiple layers that can

[19] WHO (2014). Gender, Climate Change and Health. Geneva: World Health Organization. https://apps.who.int/iris/handle/10665/144781

be toggled on and off, allowing users to focus on specific indicators such as urban heat hazard, vulnerability, exposure and possible adaptation and mitigation actions. Clear legends, tooltips, and a consistent layout ensure that users can navigate the application with ease and interpret the outputs effectively.

The service supports diverse user profiles, including local authorities, urban planners, researchers, and citizens, by offering tailored outputs and functionalities aligned with their needs. Through a user-centric design, SE4 promotes the active use of urban heat data in planning, policy development, and community engagement, empowering users to take informed actions towards climate resilience.

6.2.1.Interface and navigation workflow

The user workflow of the SE4 can be seen in Figure 86.

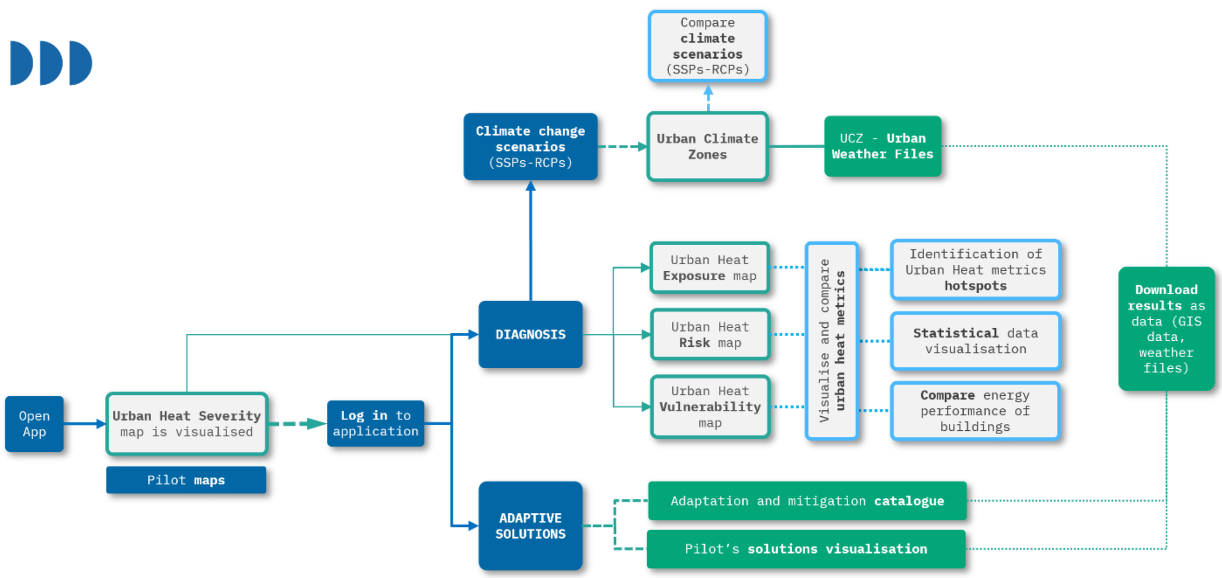


Figure 86. SE4 user workflow

When accessing for the first time, a welcome window appears on the screen giving the user the option to access the application directly or to follow a guided tour as shown in Figure 87.

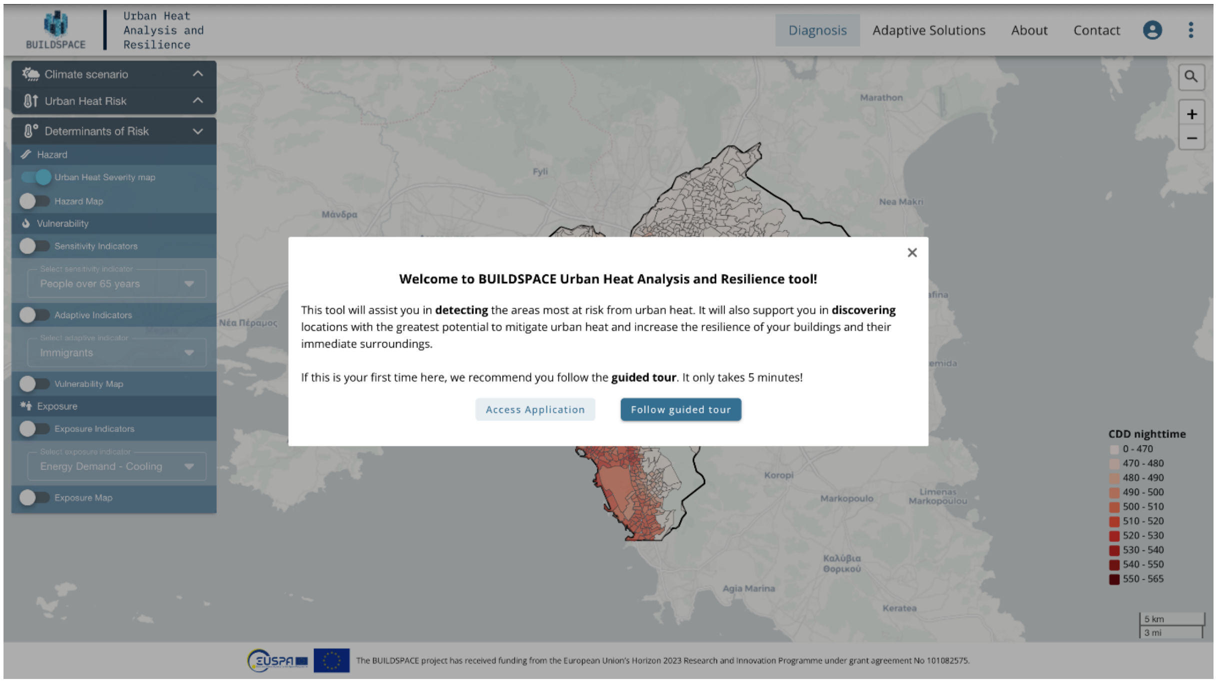


Figure 87. Welcome screen of the SE4 application

All data is listed on the left in a drop-down menu under **"Determinants of Risk"**, which includes the three components of Urban Heat Risk: **Hazard**, **Vulnerability**, and **Exposure**. In this Figure 88, only the **"Urban Heat Severity map"** is activated under the **Hazard** section. A high-resolution interpolated map is displayed, showing urban heat severity using **Cooling Degree Days (CDD night-time)** as the selected metric. The intensity is visualised through a red colour scale, and the same data can be explored at the level of administrative zones.

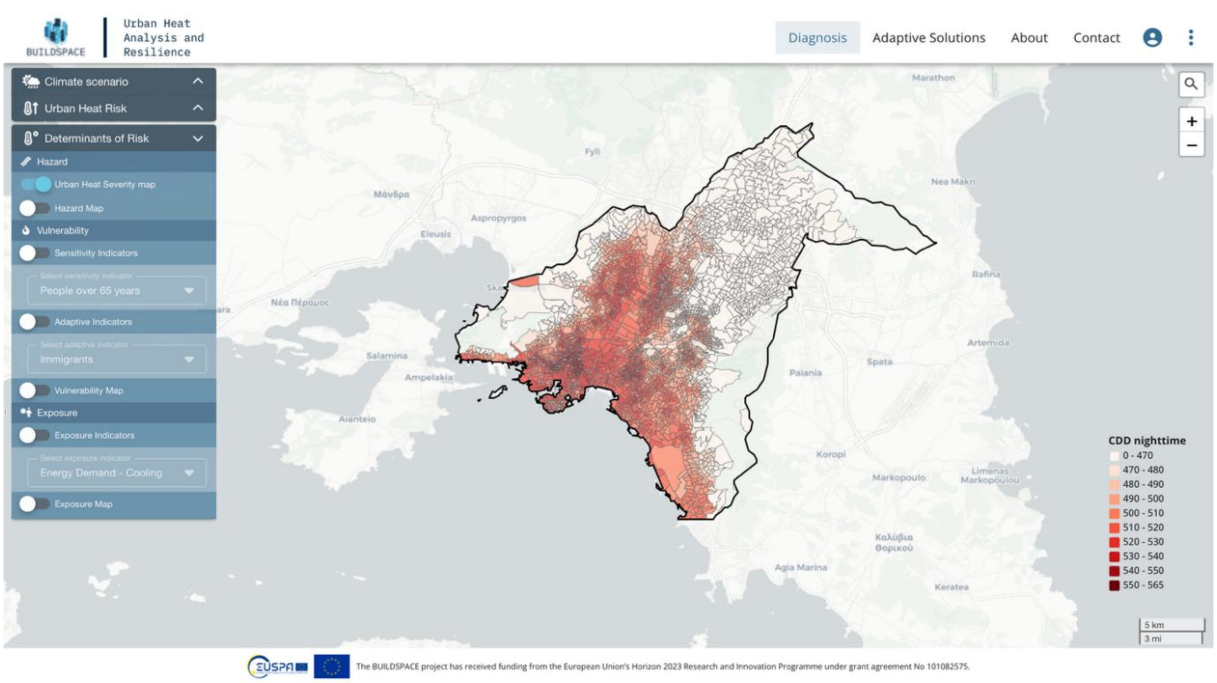


Figure 88. Urban Heat Severity Map (CDD Night-time)

The SE4 application offers a dynamic way to visualize urban vulnerability through demographic indicators. In this case, the **"People over 65 years"** sensitivity indicator is selected from the **"Vulnerability"** section, triggering a color-coded map that highlights the percentage of elderly population per district (Figure 88). When the user hovers the cursor over a specific area, a pop-up appears showing the exact percentage and how it compares to the municipal average (Figure 89). By clicking on a district, a detailed info panel expands at the bottom of the screen, providing age-specific population breakdowns and a bar chart for deeper analysis (Figure 90). Additionally, the drop-down menu visible in the interface allows users to choose among other indicators—such as **"Households with single women over 65 years old"** or **"One-member household"**—enabling a tailored assessment of different social vulnerability factors (Figure 91).

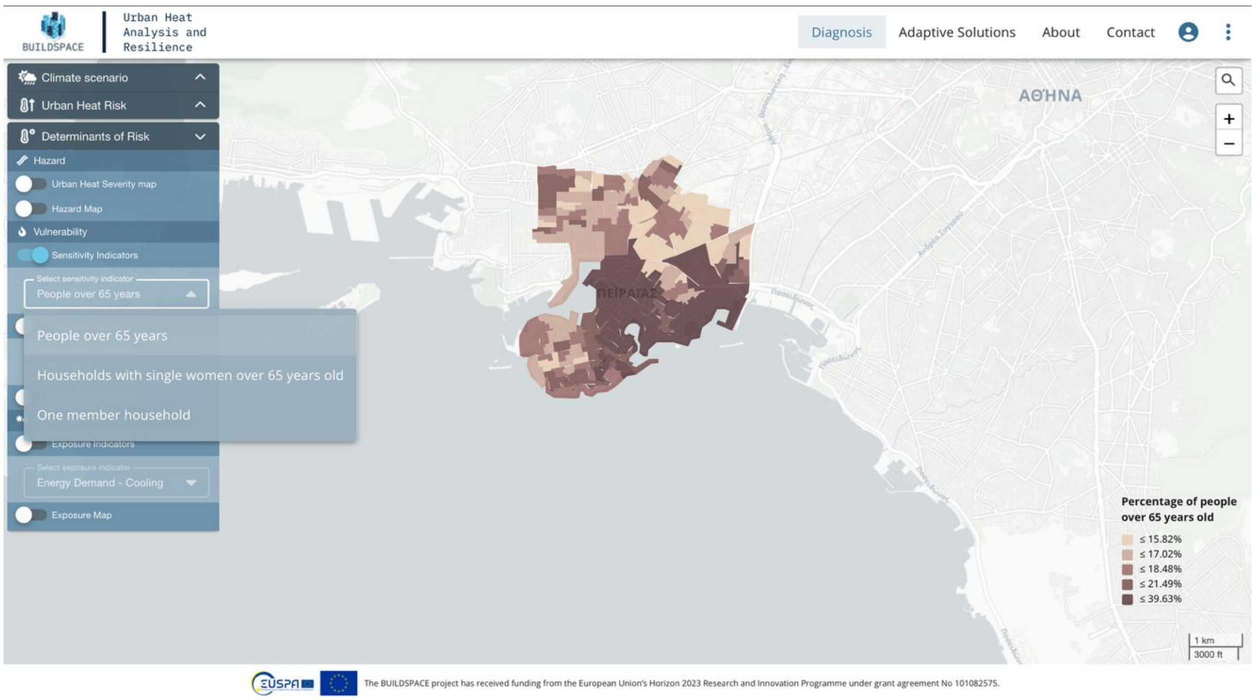


Figure 89. Sensitivity Indicator Selection

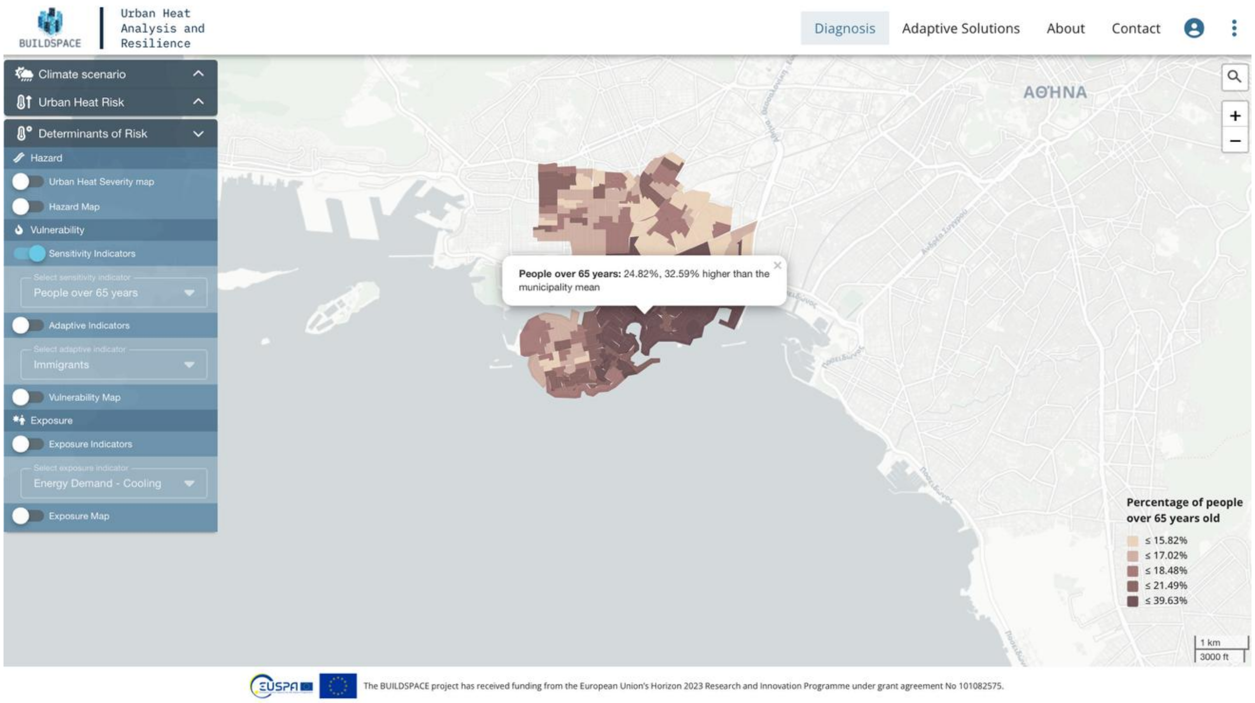


Figure 90. Hover Tooltip for Elderly Population Proportion

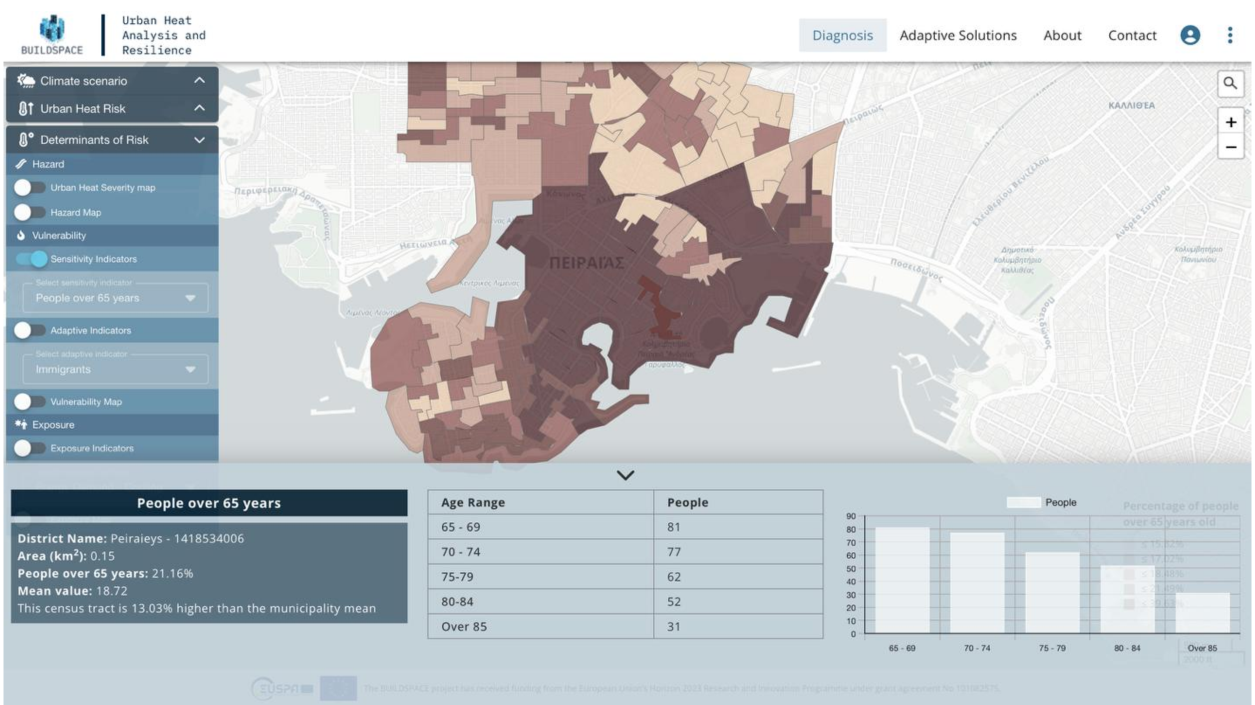


Figure 91. Detailed Vulnerability Data Panel for Piraeus District

6.2.2.Key functionalities

SE4 offers a set of key functionalities aimed at assessing and addressing the impacts of urban heat at both micro and macro scales. Its main features include:

- **High-resolution urban heat risk assessment**: Integration of urban heat exposure, socio-economic and demographic vulnerability, and population density to produce detailed Urban Heat Risk (UHR) at a fine spatial resolution.
    - *Use case: Municipalities and urban planners can identify heat-vulnerable neighbourhoods and prioritise interventions such as greening strategies or the establishment of cooling shelters and tailor them accordingly to the citizens vulnerability characteristics and needs.*
- **Urban Climate Zones (UCZ):** Identify zones with similar climatic conditions. For each one of this UCZ, weather files (datasets containing hourly climate data used in building simulations to assess energy performance in buildings) are available for current and future climate scenarios at two timeframes: 2050 and 2080.
    - *Use case: Urban designers, academics, researchers, technicians, can use these weather files in Building Energy Modelling assessments.*
- **Building energy demand estimation under current and future climate scenarios**: Estimates the energy (cooling) demand of the city's building stock under current and projected climate conditions.
    - *Use case: Policy makers and housing departments can identify high-demand buildings and target them for efficiency improvements or funding support programmes.*
- **Decision support for adaptation and mitigation strategies**: SE4 provides a catalogue with technical information for each adaptation and/or mitigation solutions such as possible limitations for implementation and recommendations.
    - *Use case: Urban planners can develop neighbourhood-specific adaptation and mitigation solutions accordingly to the needs.*
- **Use of open and interoperable data sources**: Ensures replicability of the service in other European cities by relying on open-access data such as OpenStreetMap, Copernicus products, ERA5 and CORINE Land Cover.
    - *Use case: Local administrations or city networks in other regions can apply the service with minimal adaptation, facilitating knowledge transfer and scalability.*

6.2.3.Target users and added value

The SE4 offers a decision support tool for various user groups that are included in Table 16.

Table 16. Added value of the SE4 for different user groups

User type	Added value of the SE4 Urban heat analysis and resilience

Policy makers and urban planners	- Identify urban heat risk hotspots and social vulnerability to heat, to prioritise areas of intervention.
	- Guide to climate adaptation and mitigation efforts at both neighbourhood and building scales, e.g.
	    - Countermeasures at municipal level
	    - Policy for opening public buildings as climate shelters
	    - Policy for municipal buildings retrofitting for decreasing energy demand
	    - Prioritise assistance to vulnerable people during extreme heat days
	    - Policy at municipal level for assisting the residents of the most energy demanding buildings to apply for EU/national funding

User type	Added value of the SE4 Urban heat analysis and resilience
	- Simulates the impact of climate change on cooling demand using CMIP6 scenarios (SSP126/SSP245/SSP370/SSP585) in two time-frames: 2050 and 2080.
Scientists, urban researchers and consultants	- Offers map-based results that can be used as a start point to investigate the effects of urban heat on local climates and communities with the possibility to compare these findings across European cities. - Available weather files for current and future climate scenarios (CMIP6: SSP126/SSP245/SSP370/SSP585) for two time-frames: 2050 and 2080, generated based on in-situ collected data that can be used in building energy simulations.
Citizens and non-expert users	- User friendly tool that allows explore different adaptation and mitigation solutions that can easily be adapted by the citizens. - Provides a simple, visual interface to explore building energy performance in their neighbourhood. - Rises awareness on urban heat impact and how to adapt and mitigate at different scales (city, neighbourhood and human scale).

6.3.Adaptation to pilots

The adaptation of the SE4 service to the pilot site of the Municipality of Piraeus was carried out in two keys phases. The first phase took place during the results analysis stage. After the initial outputs were generated – assessing Urban Heat Risk and its three components (hazard, vulnerability and exposure)- the results were presented to municipal technicians for validation. This step was essential to ensure that the evidence-based findings were aligned with the lived reality of the municipality. While the data used was robust, it was recognised that certain local dynamics might not be fully captured by available datasets. Through direct engagement with the pilot, adjustments were made, particularly in the statistical representation of vulnerability data, to better reflect socio-economic conditions and spatial particularities of Piraeus.

The involvement of the Municipality of Piraeus was continuous and proactive throughout the adaptation process. Their insights ensured that the service was not only scientifically sound but also locally relevant and practically applicable. This collaborative approach has strengthened the alignment between data-driven analysis and on-the-ground realities, increasing the potential impact of the SE4 in supporting climate adaptation planning at the local level.

6.4.Technical developments – Final version

For the final technology release, SE4 focused on refining and adjusting functionalities already delivered, as well as finalising and integrating those that were still under development. The following are the key technical advancements achieved in this phase:

- **Vulnerability assessment:** Adjustments in the visualisation from the statistical point of view, also integrating colour criteria to plot scientific colour maps readable both by colour-vision deficient and colour-blind people.
- **Exposure assessment:** Second iteration for the identification of exposure hotspots based on the updated building density maps. Building Energy Demand maps were calculated using the climate files created based on the CWS.
- **Identification of the Urban Climate Zones (UCZ):** Created by grouping areas with similar thermal conditions based on Cooling Degree Days and Heating Degree Days. The goal was to identify climatically homogeneous urban zones.
- **Weather Files:** For each one of the UCZ, weather files were created using a Reference Year based on CWS data. These were constructed for the current and future climate scenarios using the latest IPCC model CMIP6 (SSP126/SSP245/SSP370/SSP585) for two time-frames: 2050 and 2080.
- **Adaptation and mitigation tool:** Integration of a catalogue and a viewer with urban heat adaptation and mitigation solutions for three scales: city, building and human scale.
- **Replication and scalability enhancements:** During this last phase, a document has been prepared listing the minimum indicators and data needed to develop the service. This has been disseminated among the other pilots of the consortium to test the availability of this data in other European cities.
- **Integration of SE4 into the BUILDSPACE core platform:** The automated deployment of the SE4 service on the BUILDSPACE infrastructure was implemented based on Kubernetes. This includes both the main application and the GeoServer instance it depends on, with a secure proxy protecting GeoServer from direct external access. This approach ensures consistency across environments, simplifies operations through GitOps workflows, and reduces manual configuration. By embedding security best practices and leveraging Kubernetes-native tools, we improve maintainability, scalability, and reduce the attack surface of the deployed services.
- **Improved user interface and data visualisation tools:** The user interface and data visualisation tools of the SE4 service were improved, focusing on clarity, interactivity, and responsiveness. This includes the implementation of bullet charts for more intuitive statistical representation, the ability to compare multiple census tracts simultaneously, and improvements to colour palettes and layout for better map readability. Static information windows were added for selected layers, and consistent behaviour across devices, including tablets, was ensured. To support user onboarding, a guided tour feature with screen opacity control was developed to highlight key interface elements.

The SE4 application can be accessed in the link: **https://buildspace-s4.web.app/.**

6.5.Replication and uptake potential

The SE4 has been conceived from the outset with replication potential across European cities as a core design principle. Its modular structure, reliance on open and standardised datasets, and data-flexible methodology make it suitable for deployment in urban contexts with varying degrees of data availability and digital readiness.

Key elements enhancing SE4's replicability include the use of citizen weather station data for urban heat characterisation, the integration of satellite-based indicators such as NDVI and land use data from Copernicus services, and the ability to perform socio-economic vulnerability assessments using openly available census or survey data. The service can adapt to cities with either rich or limited data environments by flexibly incorporating national, municipal or European-level data sources.

In particular, the vulnerability component has been developed using a set of indicators that can be adjusted based on data availability, ensuring that meaningful results can be produced even when detailed census data are not accessible at high spatial resolution. The methodology applied for Urban Climate Zone (UCZ) classification and the generation of weather files for current and future scenarios is also transferable to other urban contexts, supporting the expansion of energy demand simulations and resilience planning efforts across Europe.

As outlined in the previous deliverable, an early replication of SE3 (Built Environment Climate Scenarios) was undertaken in Piraeus to estimate the cooling energy demand of the residential building stock, providing a key input for SE4. This integration enhanced SE4's capacity to assess the relationship between urban heat and building energy needs. However, the replication process faced challenges due to limited availability and quality of spatial data, such as incomplete cadastral records and missing attributes (e.g., construction year, number of floors, building typology). These gaps limited the accuracy of the energy demand estimations and highlighted the critical importance of reliable building data.

To address these limitations, CARTIF, with the support of UPM, organised a collaborative Mapathon aimed at improving the OpenStreetMap (OSM) dataset for Piraeus. The event was promoted through dedicated posters and banners prepared and shared (see Figure 92). Participants included young researchers from CARTIF, students and researchers from UPM, as well as representatives from MOBICS and the Municipality of Piraeus. Besides English, the promotion of the event was also prepared in Spanish, to easily engage *Universidad Politécnica de Madrid* students.

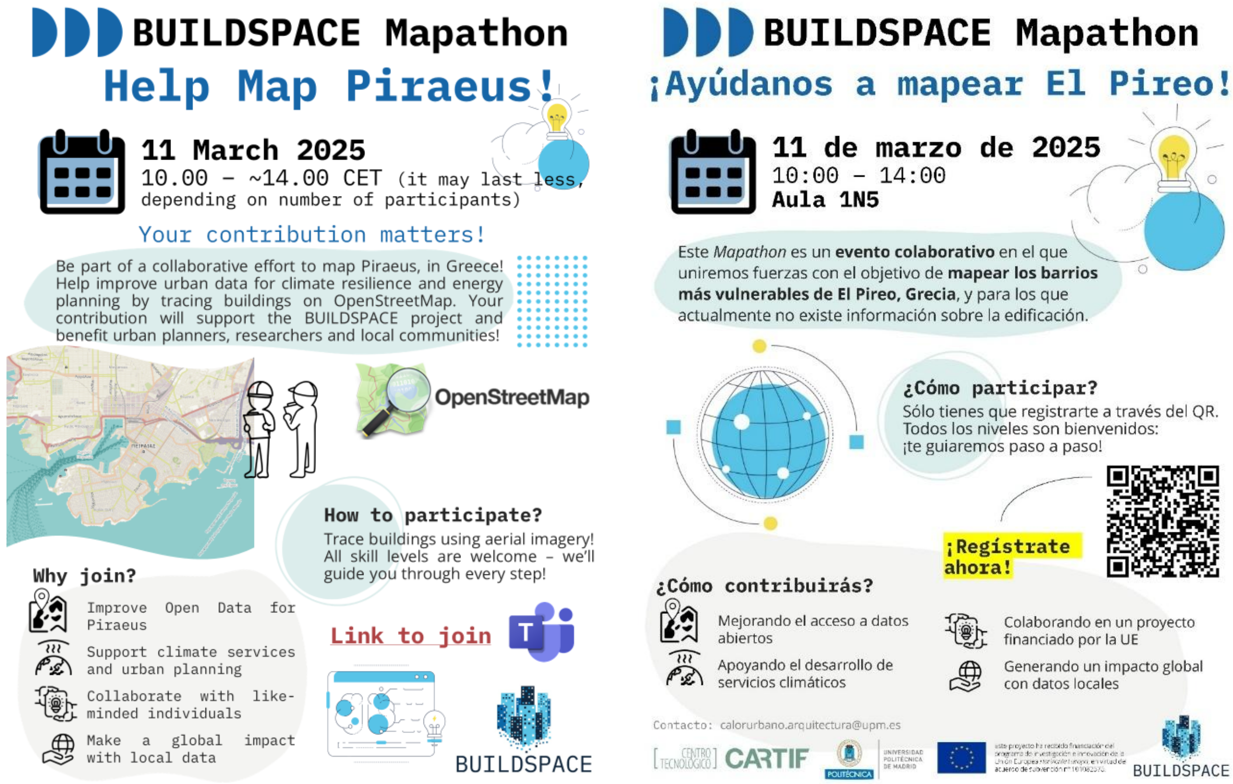


Figure 92. Mapathon posters prepared for the promotion of the event, in English and Spanish languages respectively

No prior experience was required to participate; all contributors received a short tutorial on how to edit OpenStreetMap, both before and during the event (Figure 93). The Mapathon workflow included the distribution of missing zones among participants (Figure 94), followed by a live demonstration showing how to add building footprints and attributes (Figure 95).

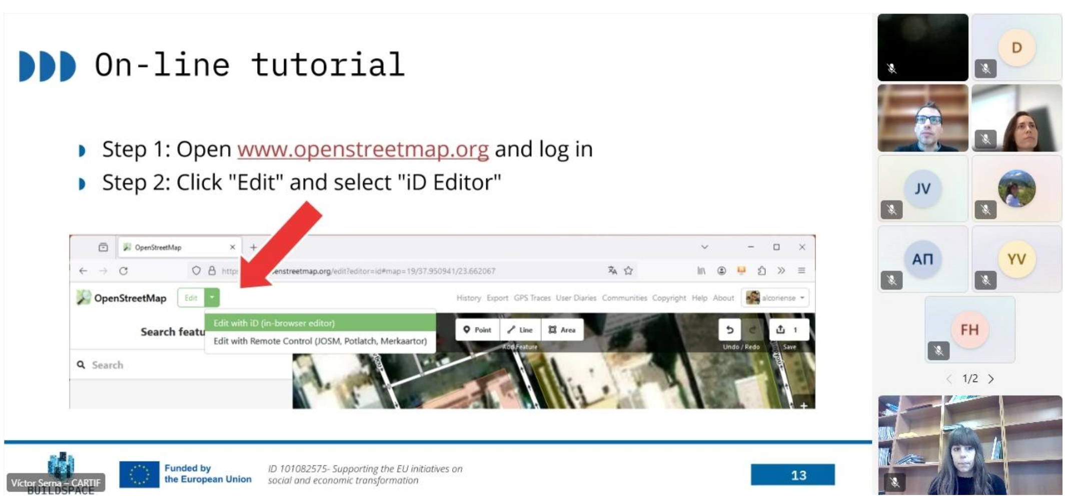


Figure 93. Screenshot taken during the Mapathon event (introduction by CARTIF team)

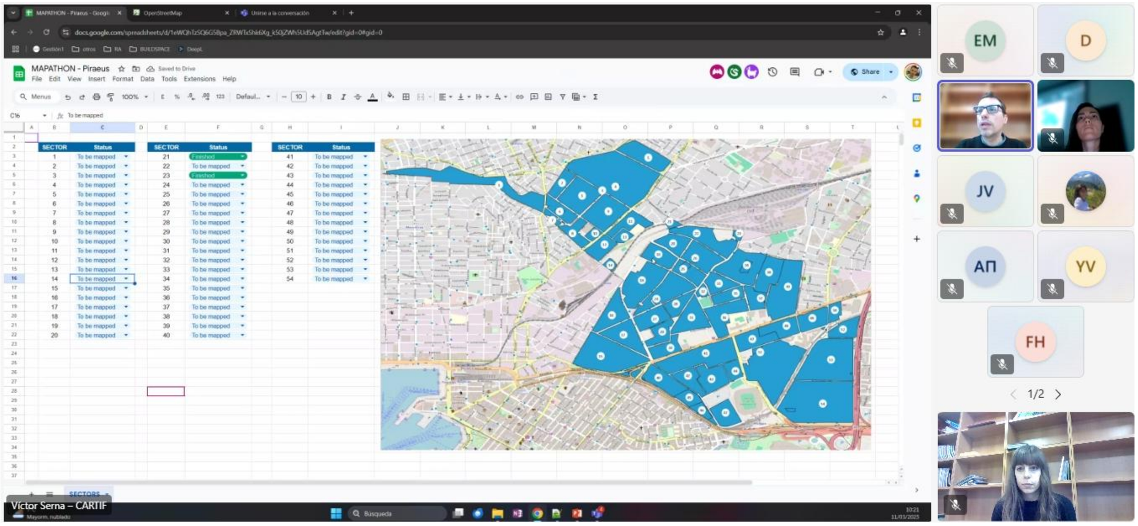


Figure 94. Screenshot taken during the Mapathon event (distribution of empty areas to complete between participants)

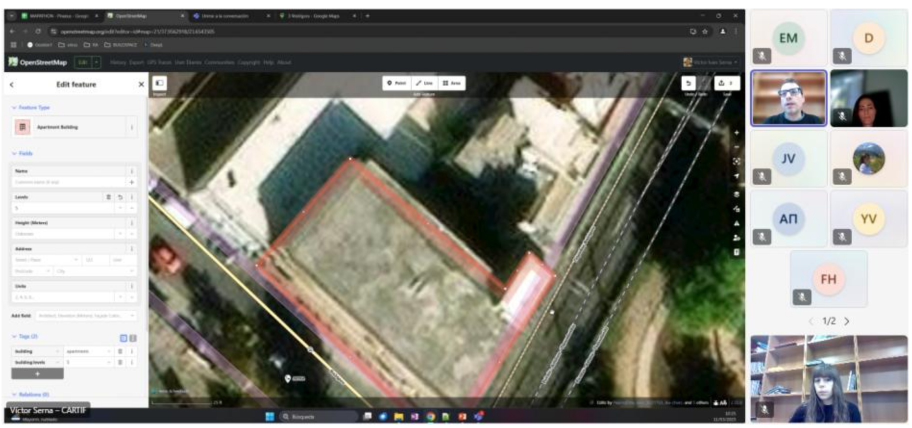


Figure 95. Screenshot taken during the Mapathon event (practical live example of how to add buildings)

Despite the strong engagement and collaborative spirit, the extend of the missing data made it impossible to fully complete the mapping in a single session. Nevertheless, the Mapathon served as a constructive learning experience, helping participants appreciate the value of urban data and the time-intensive nature of spatial data enhancement. The results were tangible: several previously empty areas in the OSM dataset were enriched, and the before-and-after comparison clearly illustrates the improvement (Figure 96).

The Mapathon proved to be a highly valuable initiative. It not only improved the quality and coverage of building stock data in the pilot area but also fostered awareness, engagement, and capacity-building among participants—particularly regarding the use of open-source tools for urban data enhancement. Moreover, the activity served as a testbed for exploring tools and methodologies with strong potential to help overcome data availability limitations in similar contexts. However, it also highlighted the critical importance of municipalities taking proactive steps to ensure access to comprehensive and up-to-date building data, which remains essential for effective analysis and evidence-based decision-making in projects like BUILDSPACE.

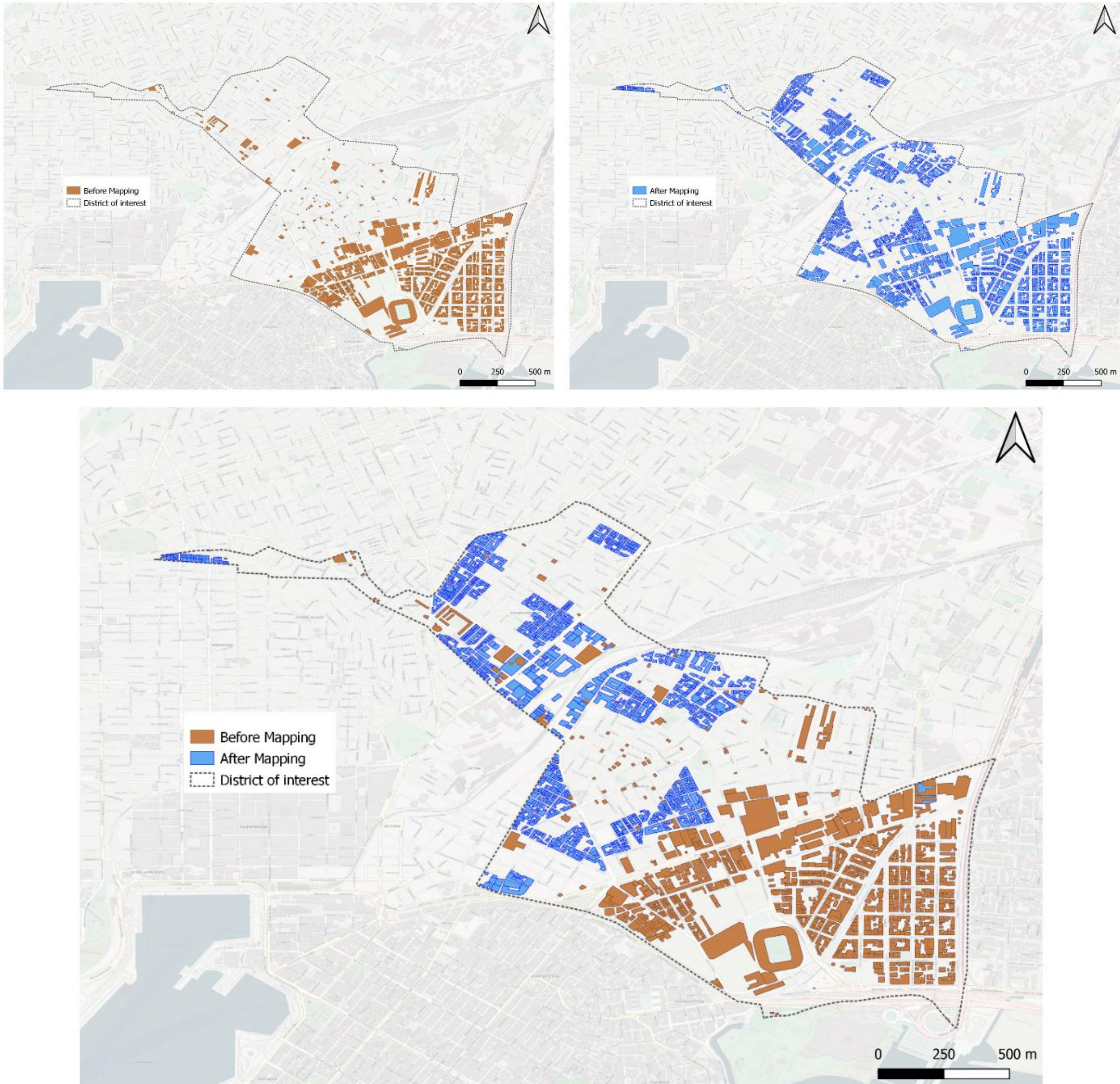


Figure 96. Visualisation of the Piraeus OSM information in lacking areas before the Mapathon (brown colour), and how it looks like after the Mapathon completion (blue colour)

7. BUILDSPACE service SE5 – Urban Flood Analysis and Resilience (city scale)

Urban Flood Analysis and Resilience (SE5) provides an interactive, map-based calculations to assess expected flood damage to buildings and flood vulnerability hotspots with hydrological impacts of blue-green infrastructure (BGI) under current and future climate conditions by using advanced analysis and visualization tools.

In this way, SE5 offers a decision support service integrating geospatial data, simplified economical and hydrological models and future climate scenarios to assist urban stakeholders in planning the maintenance and retrofitting of buildings against the risk of climate change.

The service is operated by a user-friendly web tool with a coloured map and different types of graphs as the basis for delivering the information in a very visual and easy-to-use way.

7.1.Input and output

The Urban Flood Analysis and Resilience service combines multiple data sources to provide analyses that support urban flood resilience at building, neighbourhood and city scale. This section summarizes the key inputs and resulting outputs.

Input data:

- **Building and urban data.** Buildings' geometry (boundary and area) obtained from cadastral sources or OpenStreetMap (OSM), Consolidated Cadastre of Public Infrastructure, Registry of spatial units, Land use and Planned land use.
- **Flood maps extend and flood depth data.** Hydraulic-hydrological data for characteristic return periods of 10, 100 and 500 years (Q10, Q100 and Q500), from existing flood models are offered as scenarios of flooding area. Flood depth is optional data that can be included in the calculation of flood damage values. However, calculations can also be provided without it, using the default value.
- **Flood damage data.** Flood damage values have been obtained based on a simplification of the basic method, equations and parameters, using Building and urban data listed above.
- **Blue-green infrastructure impact data.** Blue-green infrastructure impact is modelled through runoff calculations using Copernicus Urban Atlas Cover (UAC) as a base for the calculations. CORINE Land Cover was used for the classification of land into different land-use categories to make the connection between UAC and runoff parameters. Sentinel-2 MSI Level-2A data and Normalized Difference Vegetation Index (NDVI) were used to determine land use and urban areas. Fieldwork was conducted to verify the data about the extension scope of urban green areas.
- **Climate data.** Climate-driven hydrology scenarios were generated including analysis of historical precipitation data, analysis of future precipitation data, and providing future climate change scenarios RCP2.6, RCP4.5 and RCP8.5 IPCC scenarios for pilot area.
- **Retrofitting strategy definitions.** A catalogue of BGI renovation measures is included in the service, covering buildings' exterior and their surroundings such as green roof, green wall and rain garden. Users can apply one or more measures to simulate their hydrological impact allowing a

comparison under current and future climate conditions. These scenarios directly affect the buildings and its surrounding's runoff properties in the model, updating its estimated performance.

Outputs:

- **Flood damage analytics.** The service calculates and visualise in a coloured georeferenced map the expected flood damage to buildings to identify flood vulnerability hotspots in terms of flood damage. It produces spatially detailed flood damage expected estimates expressed in € per flood event per selected urban area on a Damage Layer.
- **Urban runoff analytics.** The service simulates rainfall runoff to identify urban flood vulnerability hotspots with hydrological impacts from BGI. It produces spatially detailed urban runoff estimates expressed in mm per rainfall event per selected urban area. Results are displayed as colour-coded maps using 5 mm reference rainfall runoff principle as a runoff norm for urban areas[20] on a Runoff Hotspot Layer.
- **Scenario explorer and comparison mode.** On Flood Damage Estimation mode user can select from three different flood scenarios from three different return periods flood (10-year, 100-year and 500-year), they can also choose to simulate either climate change, which will expand the flood extent by 30m, or incorporating anti-flood measures, that will decrease the extent by 50m. On Urban Runoff Simulation mode user can select the precipitation value from three different IPCC climate change scenarios (RCP2.6, RCP4.5, and RCP8.5) and three projection years (2040, 2070, and 2100). When a user has chosen a desired flood/precipitation scenario, the scenario will be used in the next damage/runoff calculation.
- **Retrofitting simulation results.** A catalogue of different BGI measures with condition instructions for building renovations is included and three retrofitting scenarios are available for the user to select and compare. User can compare baseline and future performance, as well as pre- and post-retrofit states.
- **Visualisations.** The Damage Layer and Runoff Hotspot Layer can be visualized in two ways on the map. One uses fixed categorical classes (Excellent, Good, Sufficient, Problematic) for consistent cross-area comparisons. The other uses a continuous, relative scale specific to the analytics layer, highlighting detailed variations within the area of interest. The maps are recalculated dynamically depending on the selected flood or precipitation scenario, climate-change scenario, retrofit scenario and timeframe.
- **Aggregated statistics and data panels.** A bottom panel dynamically summarises all buildings within the selected research area, i.e., the analytics layer. The distribution of the layer classes is shown in graph and table form. Metrics include the size of the survey area, the number of buildings, total flood damage/average infiltration level, sum of damage costs/ area rainfall runoff (flash flood risk) and its distribution per damage class/runoff class. This provides a quick overview of building stock urban flood resilience performance at different spatial scales.

[20] Klemen et al. 2024. Innovative tools to promote and assess the hydrological impact of blue-green infrastructure measures on the urban water cycle (http://www.urbaniizziv.si/portals/urbaniizziv/kompletni_pdf/uizziv-20-2025-strokovna_web.pdf)

SE5 provides a decision support service that allows users to interact with maps and select different climate and retrofitting scenarios in order to evaluate resilience to urban flooding. Figure 97 summarizes the workflow of SE5.

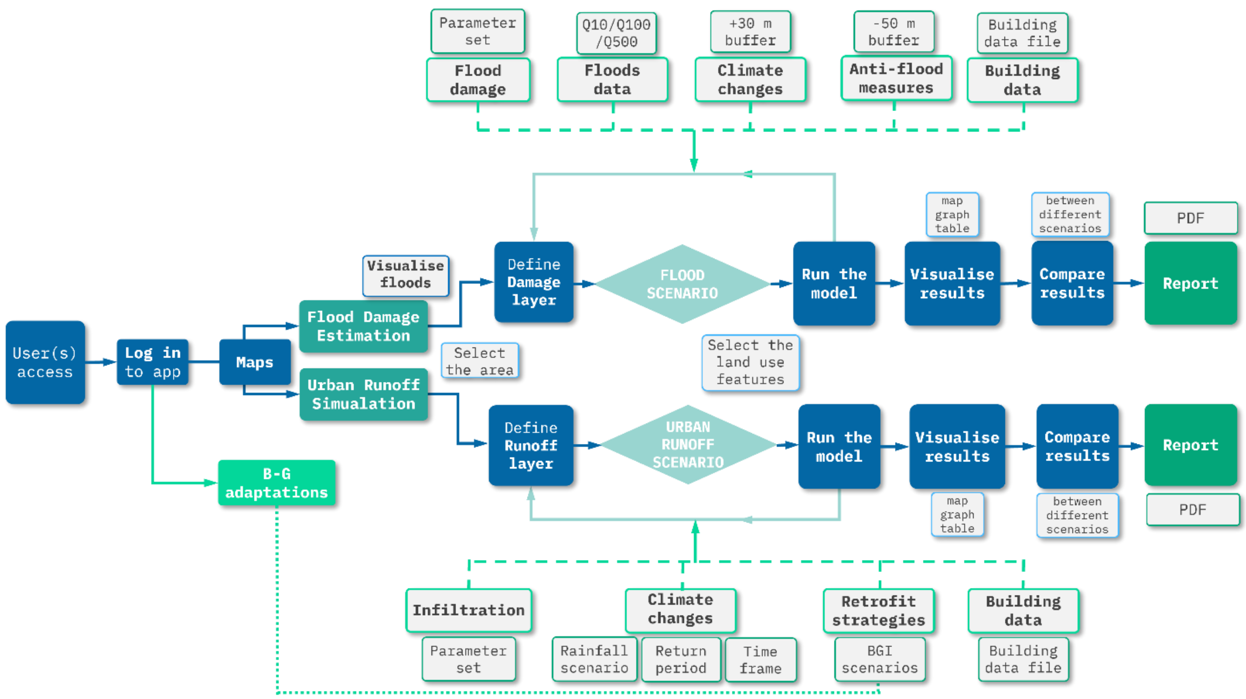


Figure 97. Workflow of SE5

7.2. User experience

The development of the SE5 has been designed from the outset with usability, functionality and friendliness for a wide range of stakeholders in mind. The service is accessed through an intuitive user-friendly web interface designed around a city-scale map, where individual buildings are visualised as colour-coded polygons based on their estimated flood damage and/or urban runoff values, which are considered two different 'modes'. This enables the quick identification of buildings and neighbourhoods with inadequate urban runoff performance. In addition, our priority was to ensure scalability and replicability in other European cities and beyond.

7.2.1. Interface, navigation workflow and key functionalities

7.2.1.1. General structure and functionalities

To access the application, a user needs to log in to get identified and access. The login screen pops up automatically and all other buttons and functions are disabled. The user needs to provide their email address as a username and a correct password. If the user does not want to enter his credentials every time he opens the application they can check the 'Remember login' checkbox. When the credentials are filled in and correct, the user needs to click the 'Login' button. If the credentials are not valid, a warning message will appear. If a user does not have an account yet, he can click the 'Sign-up' link to create an account by entering an email address and a password. After email verification, access to the application and all its functionalities will be granted to the user.

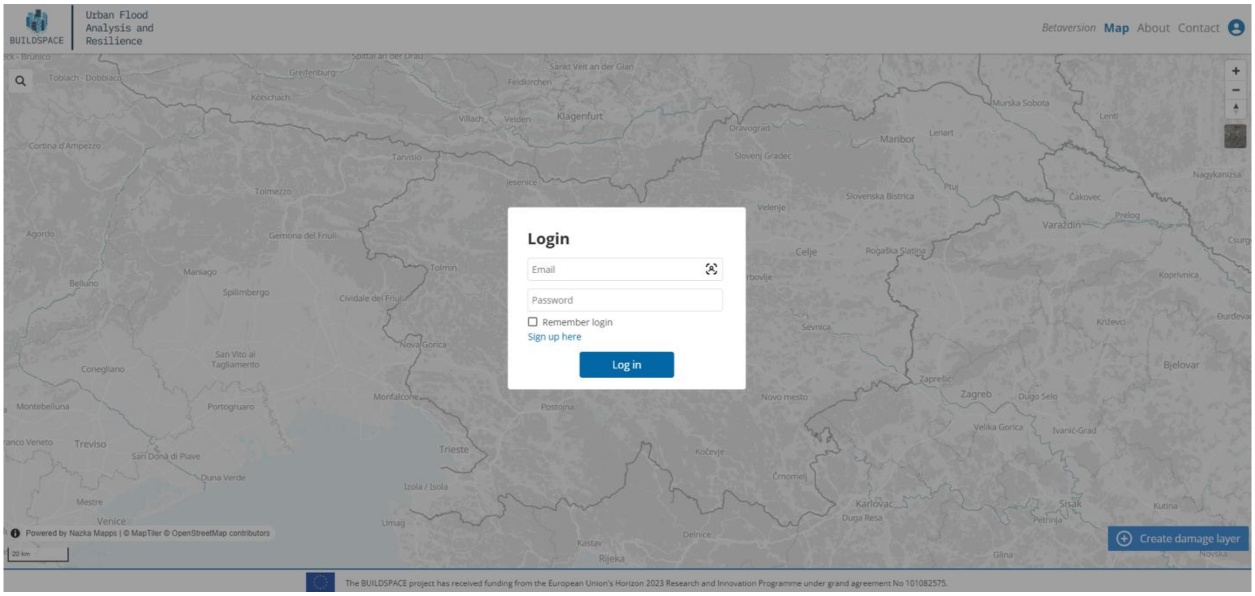


Figure 98. SE5: Login screen

After user logs in, another window opens over the map (Figure 99). This pop-up obliges to choose the mode you would like to access. There are two options: the river flood damage mode and the flash flood hotspot simulation. The user needs to click the blue 'Select' button underneath the corresponding mode description.

Figure 99. SE5: Mode selector

When a mode is chosen, the name of the mode is shown on top in the navigation bar as can be seen in Figure 100. Next to the mode name, there is blue button that when clicked, will bring the user to the other mode for easy intra-mode navigation.

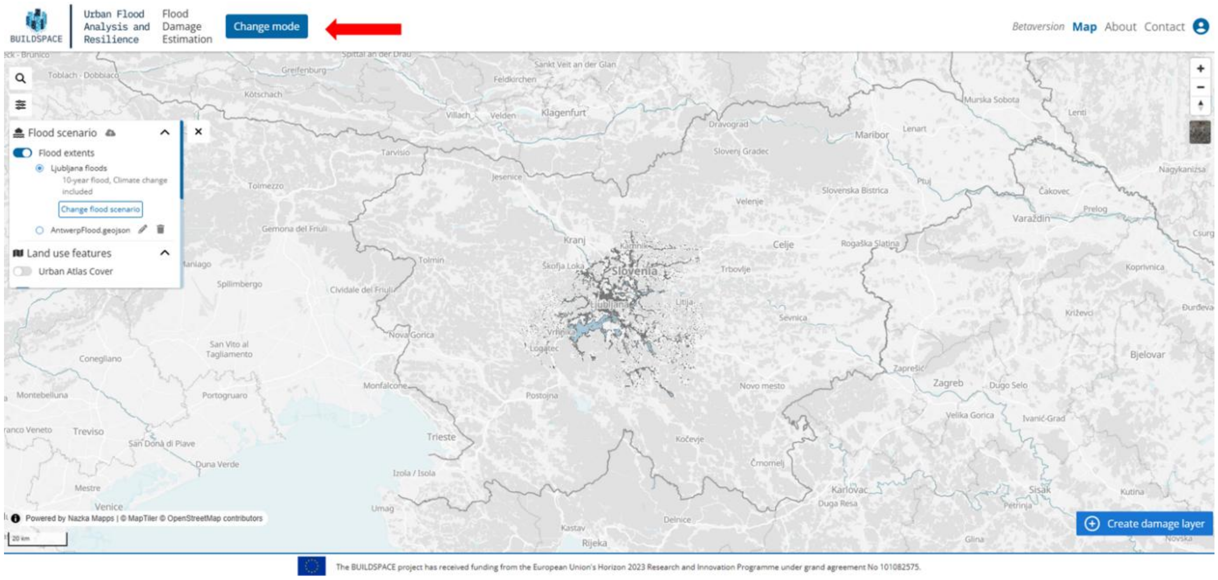


Figure 100. SE5: Changing application modes

When the user is logged in and have chosen a mode, the application will appear. As can be seen in Figure 101, the map is the most important component. The map has some basic controls to operate with. For zooming, the user can use the mouse wheel to scroll or use the **+** and **–** buttons at the top right corner. The pan and move the map around, the left button on the mouse can be held to drag the map in the desired direction. If the right button of the mouse is held, the map can be titled vertically or turn it around its axis. The north arrow at the top right will change direction depending on the movements made by the user with the map. If the user clicks the north arrow, the map will reorient itself back to the north.

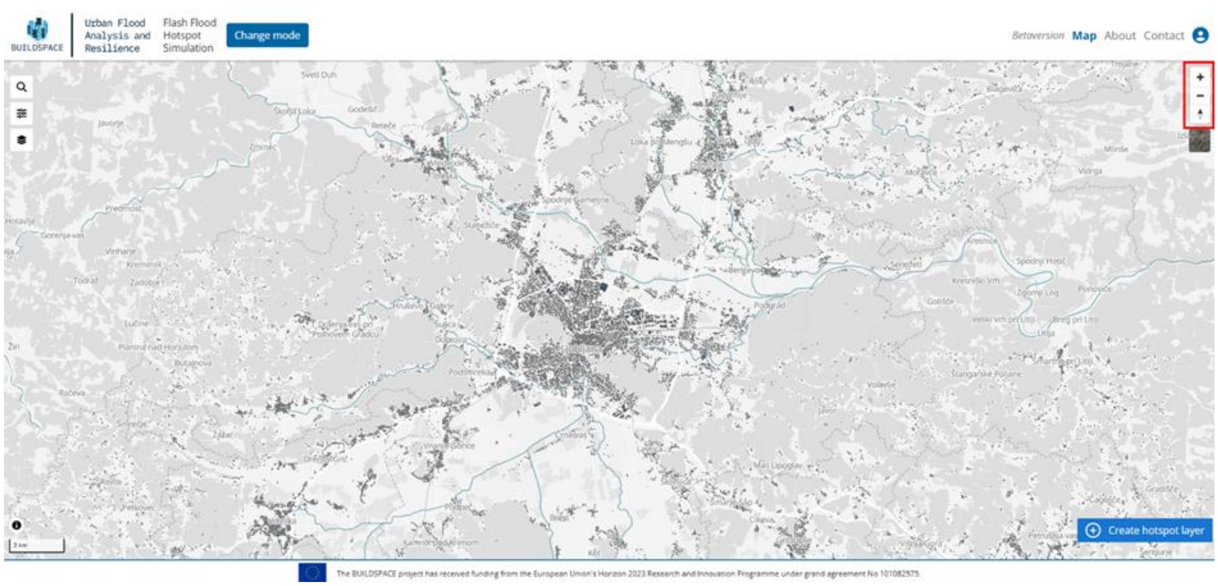


Figure 101. SE5: Basic map controls

Below the map controls there is a background selector. The background selector gives the option to activate a background layer that can assist with map navigation. When user clicks on it, a small menu opens with two options. The first option is the satellite view (Figure 102), activated when clicking the toggle next to it. Secondly, it is also possible to activate the local boundaries, this option is explained further in the replication potential of section 7.5.

Figure 102. SE5: Satellite view

On the top left, there is a search functionality (see Figure 103). The white button with the magnifying glass sign opens the search bar. Then, user can click on the search bar and type to search any location in the world. The first five options are listed in the result box, as shown in Figure 103. When the desired option is found, user can select it and the map will zoom and pan to the location. The search functionality allows for searching for both cities as points of interest. The X-icon serves to close the search bar.

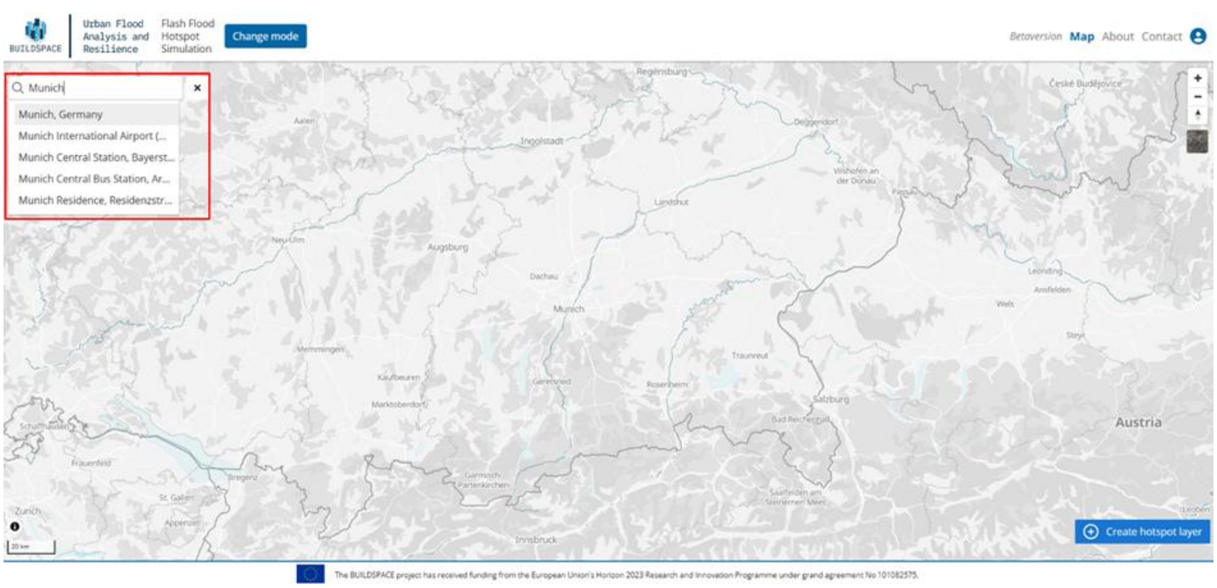


Figure 103. SE5: Search functionality

7.2.1.2. Layer panel

The layer panel is structured slightly differently between the two modes (flood damage estimation or urban runoff simulation). Generally, the layer panel can be opened by clicking on the white layer button at the top left (Figure 104). The X-icon serves to close the layer panel. The panel is structured in different parts that can be opened or closed using the upwards and downwards-facing arrows.

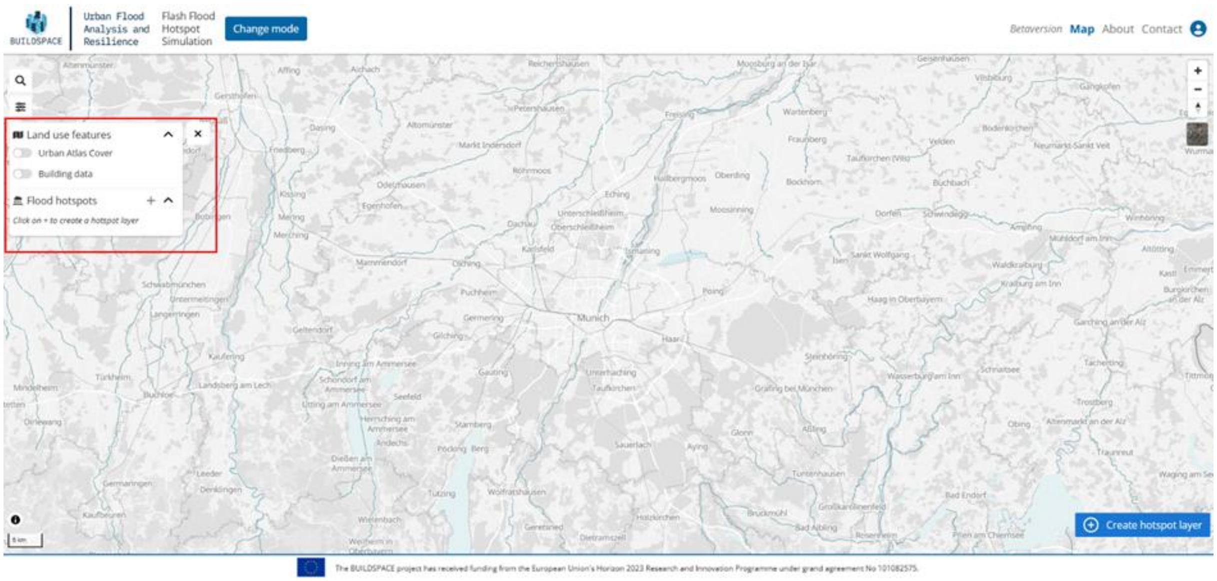


Figure 104. SE5: General layer panel structure

In the river flood damage estimation mode, the top part is to visualise flood extents of different climate scenarios (Figure 105). This part does not exist for the flash flood mode. The toggle allows the user to activate the visualisation of flood extents on the map. The flood extents will have preloaded floods for Slovenia, but a user can upload up to three custom flood extents by using the upload button. This is explained in more detail in the replication potential of section 7.5. A user can decide which flood extent to visualise by clicking the radio button before it. Only one flood extent can be visualised at the same time.

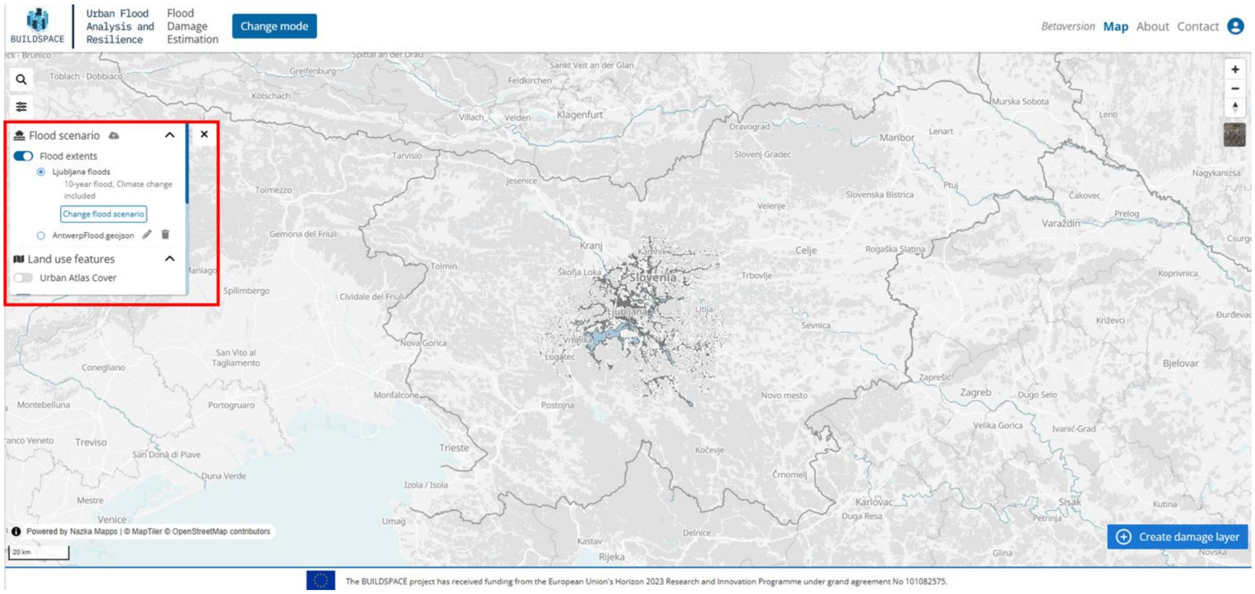


Figure 105. SE5: Flood extents in the layer panel

For the preloaded Slovenian floods, there is a button to change which flood is visualised. When this button is clicked, a panel opens over the map that allows to choose one of the pre-defined flood extents (Figure 106). There are two dropdowns that allow to pick a flood extent. In the first dropdown, user has to choose a flood return period. There are three options: 10-year, 100-year and 500-year. The second dropdown allows to change the extent depending on certain scenarios. Or either 'No scenario' is selected, which will provide the original flood extent. Furthermore, the option 'Anti-flood measures' simulates taking precautions to limit the amount of flooding. For this option, the flood extent will be diminished by 50m. The last scenario is simulating climate change by extending the flood extents by 30m. The inset map shows the option selected. When confirmed, the selected flood extent will be loaded into the main map and the pop-up will close.

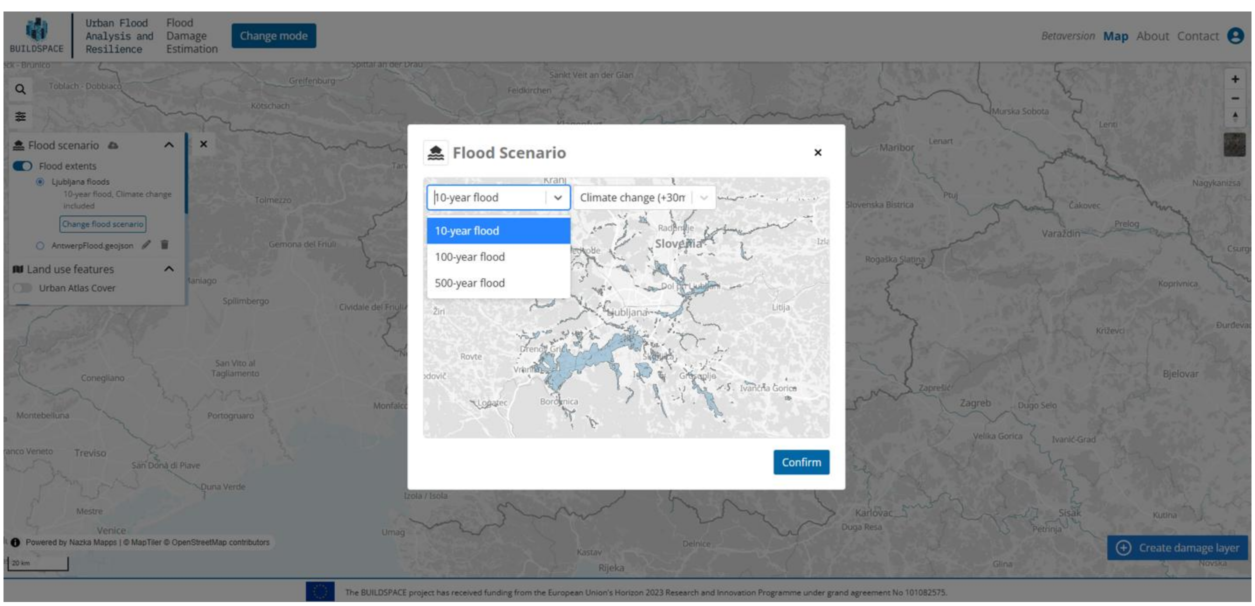


Figure 106. SE5: Changing a flood scenario

Both modes have in the layer panel a section about land use features that can be visualized and are used in the calculations (Figure 107). There are two options: the Urban Atlas Cover and the building data. The Urban Atlas Cover is a Copernicus land use classification map. If user hovers over the small info button, a legend will open on the side that shows all the categories visible on the map. In the layer panel, an opacity slider will appear which allows to increase or decrease the opacity of the layer visible on the map. When the building layer is activated, the buildings appear on the map. Here there is also an opacity slider provided. For buildings, a user can also upload their own building data, as explained in the replication potential of section 7.5.

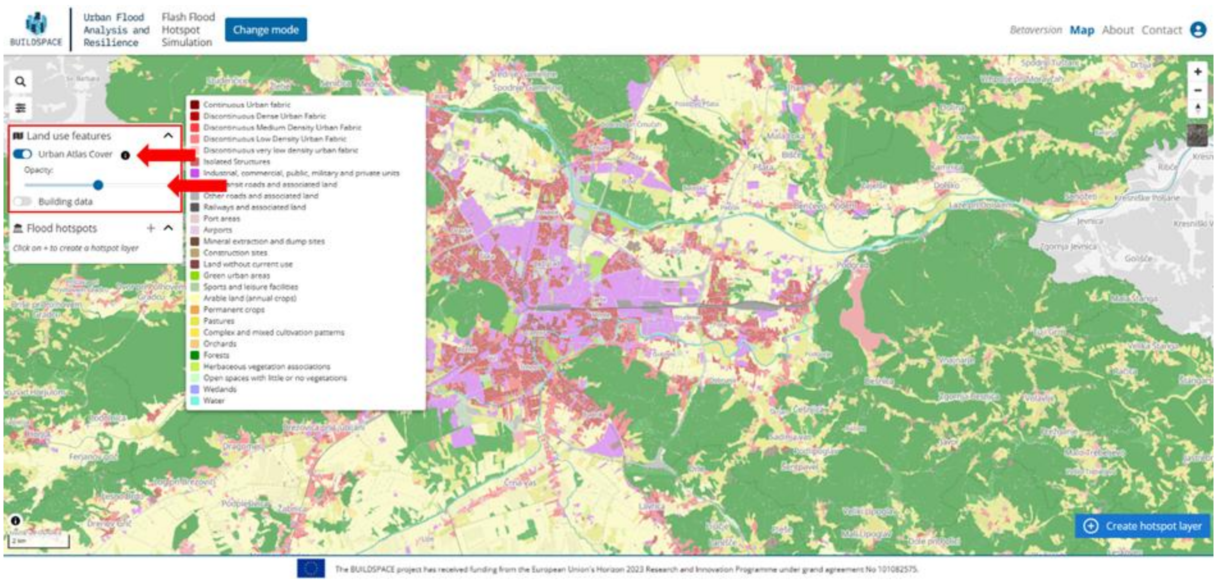


Figure 107. SE5: Land use features in the layer panel

7.2.1.3.Creating a result layer

To create a result layer in either mode, the blue button at the bottom right can be clicked, or the little plus button at the result section of the layer panel (Figure 108). This will bring user to the result layer creation view which will allow to enter all required parameters to start calculating the results. Depending on the mode, the parameters will differ.

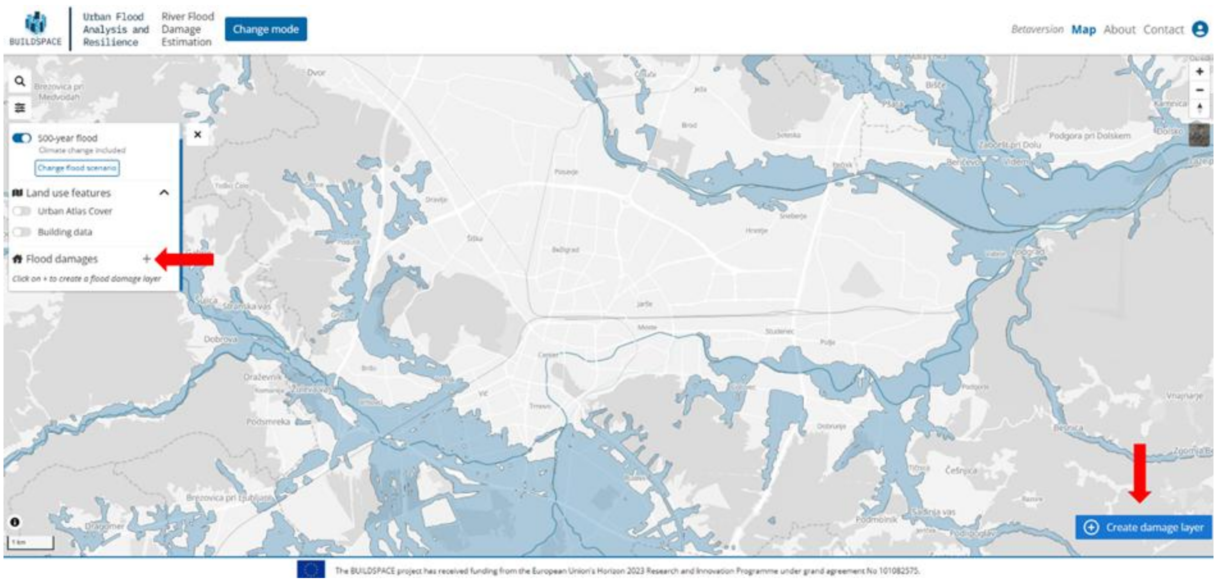


Figure 108. SE5: Start creating a result layer

When user is in the view of creating a new result layer in both modes, they will be asked to draw an area of interest (Figure 109). This is a necessary step in both modes. When ‘Draw new area’ button in the side panel is clicked, the map will go into drawing mode. At the bottom right, a new set of controls will appear in the bottom right. This will allow to draw either a circle, a rectangle or a free shape. The circle will be standard selected. To draw the circle, it is needed to first click on the map, which will set the middle point. Then when moving the mouse across the screen, the circle will appear. When clicking again, the circle will be set. For rectangles, the handling is very similar. The first click sets the bottom left corner point of the rectangle and the next click will set the top right corner point, which results in a rectangle. Finally, the free shape allows to draw any shape wanted. Each click will draw an extra node. At least three nodes are needed to be able to finalize the drawing. To complete the drawing, either the ESC-button on the keyboard or make double click on the last node can be used. The size of the area of interest is limited to 1 km^2. The application does not allow to save a larger one. When a drawing is completed, a small pop-up will appear to allow to give it a name, and then save it or delete it again. The drawing can also be cancelled and exit the drawing mode by clicking the ‘Cancel drawing’ button on the side panel.

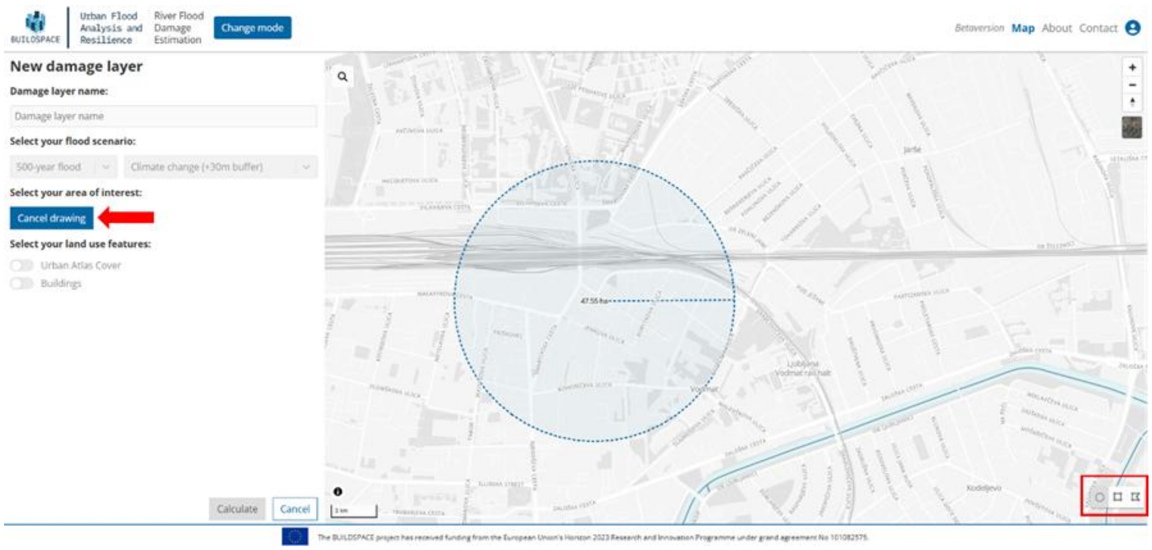


Figure 109. SE5: Drawing an area of interest

In the river flood damage estimation mode, the screen will look as shown in Figure 110. Firstly, the damage layer being created needs a name. This name will be used to save the layer to the user's profile so that it can be identified later again. Below the name, the flood scenario needs to be selected. The flood scenario currently active on the map will be filled in here, but user can still pick another one by using the two dropdowns, also their custom floods will be present in the first dropdown. Next, there is the area of interest. Here user can choose to draw a new area, as explained in the previous step, or select an area that has already been saved from the dropdown next to the button. If the dropdown is not present, that means no area has been saved to the user's profile yet. Finally, the land use features need to be selected.

On the example below (Figure 110), the buildings have been selected, this can be the standard Slovenian building set provided or a custom uploaded building set. They are visualised on the map and this means that the calculations will be done on the individual buildings. If all the requirements are entered correctly, the blue 'Calculate' button at the bottom will activate. If the button is not active, it means one of the parameters is missing. When clicking on the calculate button, the calculation will start and the resulting layer will be created and saved to the user's profile. Clicking the 'Cancel' button will take user out of this mode back to the main map without conducting any calculations.

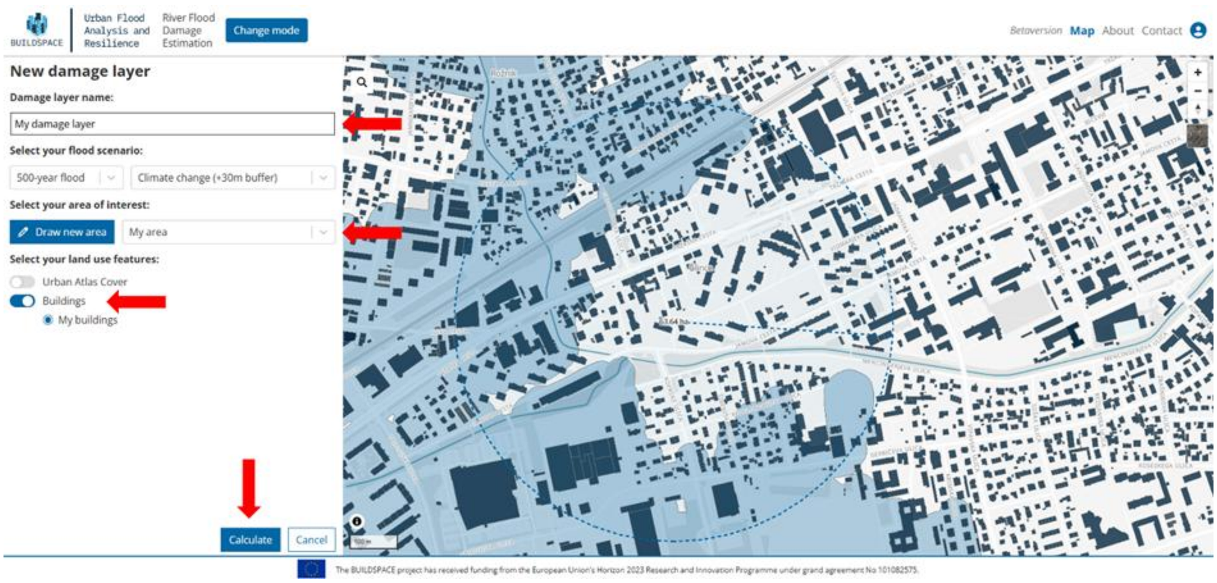


Figure 110. SE5: Creating a damage layer using a building dataset

If in the panel, in the land use features section, the 'Urban Atlas Cover' is selected, the content of the panel will change slightly as can be seen on Figure 111. In the land use feature section, all classes of the UAC that are present within the selected area of interest will be listed. There user can choose to click the checkboxes at each category to decide if they want to include that category into the damage estimations. The options that are selected, will be visible on the map. If the mouse is hovered over an area, the class will appear in a pop-up.

Above the land use features, the flood scenario section will have an extra input field: flood height. Here the user can enter the flood height they would like to simulate in meters. Any height between 0.1 meters and 10 meters can be entered. Lastly, at the bottom of the panel, user can also select their parameter set that will be used to do the calculations. In this mode, the parameter set will determine the damages in Euros per square meter for each UAC-class. User can choose to either use the standard parameter set provided, or create a new parameter set by clicking on the last option of the dropdown. When all inputs have been given, the result can be calculated, which will return a damage estimation for the selected flood for each Urban Atlas Class.

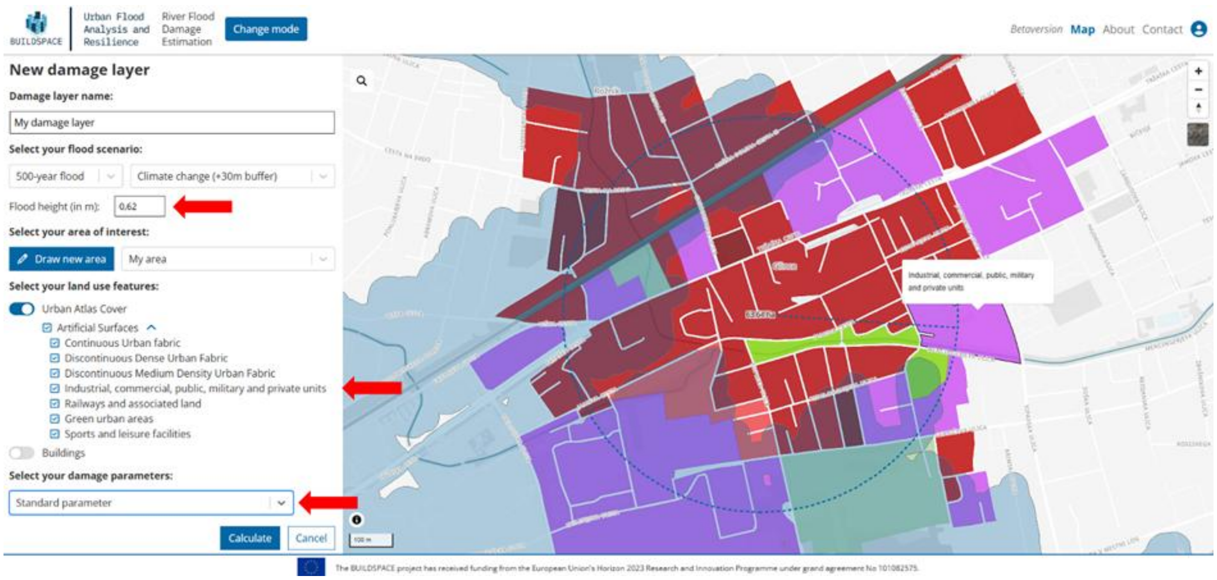


Figure 111. SE5: Creating a damage layer using the Urban Atlas Cover

The flow for creating a flash flood hotspot layer is relatively similar to the river flood damage estimations (Figure 112). Here, the user will also need to provide a name in the first box and select or draw an area of interest on the second line. There is no need to choose between the UAC and the building file in this mode, as both will be considered automatically. There is however an extra dropdown at the bottom that requires to choose which building layer to use if the user has uploaded a custom one. Here it is advised to choose the building set that overlaps with the area of interest to achieve meaningful results. For navigation purposes, a simplified layer panel is active on the map to visualize any of those layers.

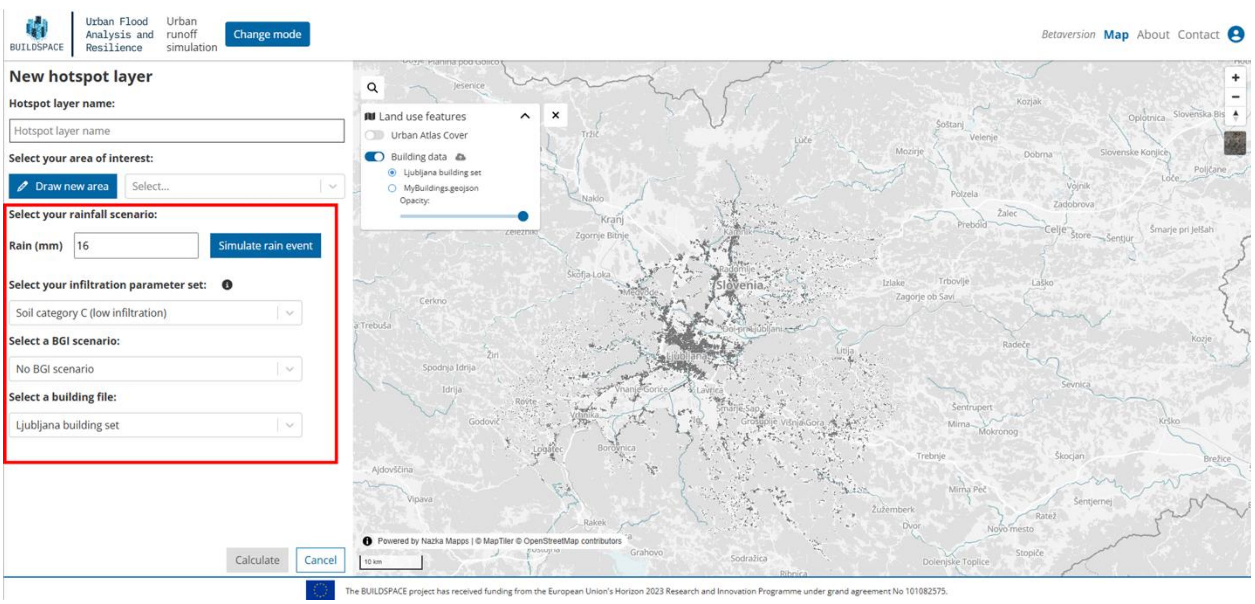


Figure 112. SE5: Creating a runoff layer

Furthermore, there are three new parameters that need to be defined (Figure 113). Firstly, user has to decide on a rainfall event. This can be done by entering the number of millimetres of rain desired to use in the calculations. In case of doubt, a handy calculation method has been included and can be accessed by clicking the 'Simulate rain event'-button. This will reveal three extra dropdowns where a climate RCP scenario, a return period and a year can be selected. Based on this input, the tool will provide an expected rainfall that can be used in the hotspot generation.

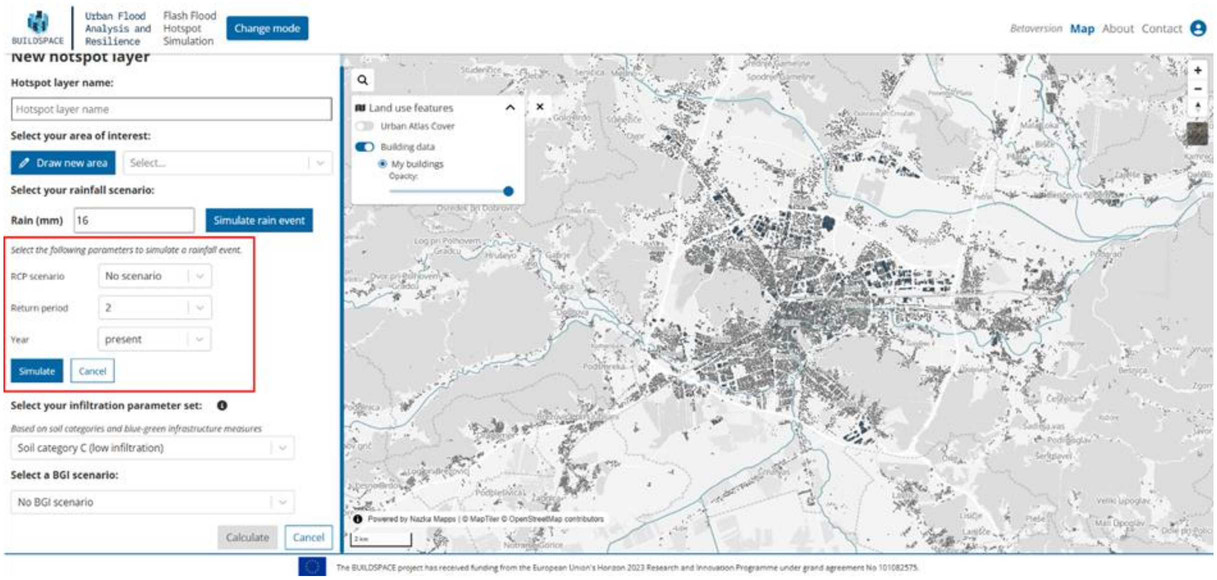


Figure 113. SE5: Estimating a rainfall event

Secondly, a soil infiltration set needs to be decided. This will set the base infiltration parameters for each Urban Atlas class depending on the soil desired to simulate. The soil classes go from class A, permeable soils such as sand to class D which are less permeable soils such as clay. Furthermore, a user can also select a custom soil parameter set, which is further explained in the replication potential of section 7.5.

Lastly, the user can also select a BGI-scenario. This will change the base infiltration parameters that has been set in the previous step relatively depending on the selected BGI-scenario.

7.2.1.4.Managing a result layer

When a result layer is created successfully, user will be redirected to the main page where results will be automatically showcased on the map. The Figure 114 shown below is for a damage layer, but there are similar for runoff layers as well. At the layer panel on the left side, the section about the results will now be filled with the created layers. This section is called 'Flood damages' for the river flood damage estimation mode and 'Flood hotspots' in flash flood mode. Here the result layers are organised and structured by area. Each area can have one or more result layers, but only one layer can be visualised at the time.

If a user clicks on the pencil icon in the title, each area and layer will receive some action icons. Firstly, there is a pencil that allows to change the name of an area or a result layer. Secondly, there is a trash can. When this is clicked next to a result layer, the layer will be deleted. If an area is deleted, the area itself as well as all result layers in that area will be deleted.

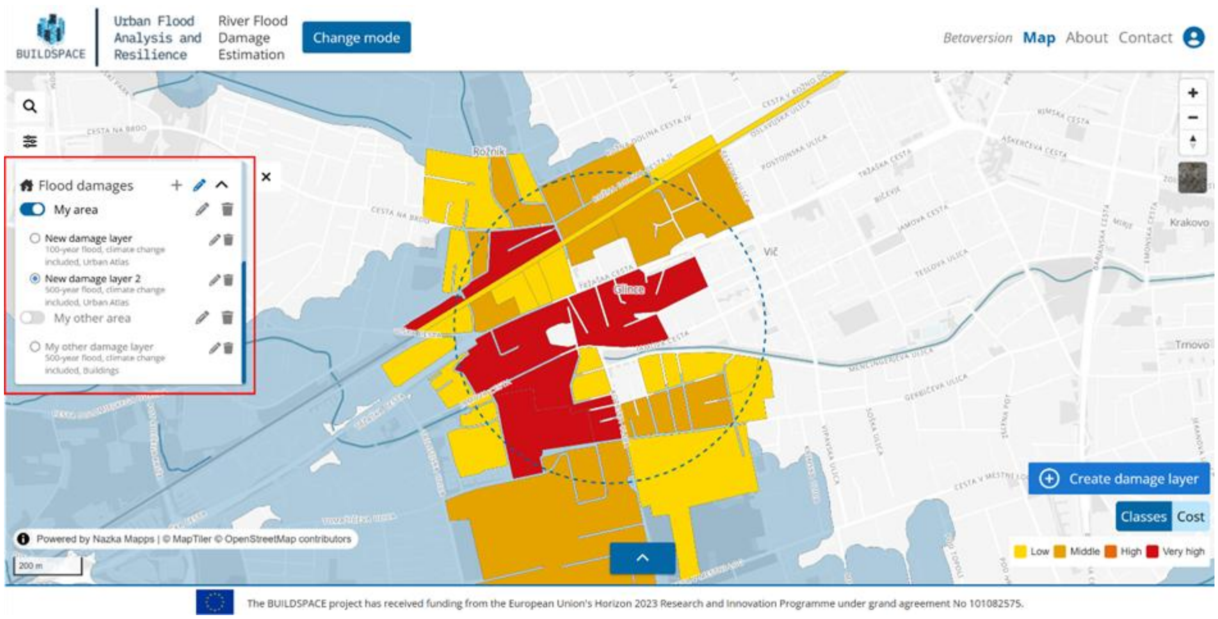


Figure 114. SE5: Management of result layer in the data panel

At the bottom left corner of the screen, a legend will be present when you have a result layer active (Figure 115). Above the legend, there is a switcher which allows you to change the visualisation. If classes are visualised, they have fixed boundaries and do not change depending on the results. This allows for easy cross-layer comparisons. For a more detailed look within the created layer, user can choose this option 'Continuous', which will create a continuous colour scale depending on the values within your result layer, ranging from the lowest to the highest value. This allows for easy intra-comparison.

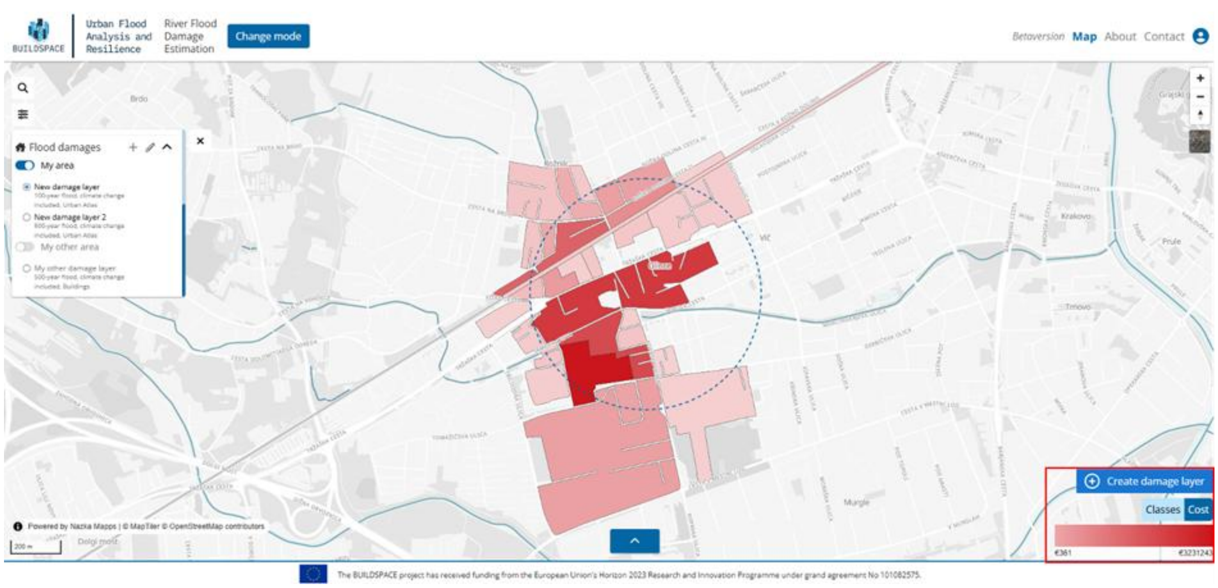


Figure 115. SE5: Legend to change visualisation mode

When a result layer is created, a data panel with extra information and analysis will be provided (Figure 116). The data panel is hidden below the screen and can be opened by clicking the white arrow in the blue button. The same button can be used to close the panel again. At the top left of the panel, there will be a dropdown that holds all result layers, grouped per area of interest. User can choose to select another result layer from this dropdown to load the data of that layer in, or they can select it in the layer selector. Next to the dropdown, there is a 'Compare scenario' button, that will start a comparison. It is discussed in the next section.

The content of the data panel itself, depends on the mode you are in but the structure is the same. On the left there are some attributes in text form of the selected result layer. On the right, there are graphs and tables showcasing the results with more detail. At the bottom of the screen, there is a little arrow that allows to navigate to the next screen of visualisations, if any are available. Navigation downwards is just done by scrolling in the data panel.

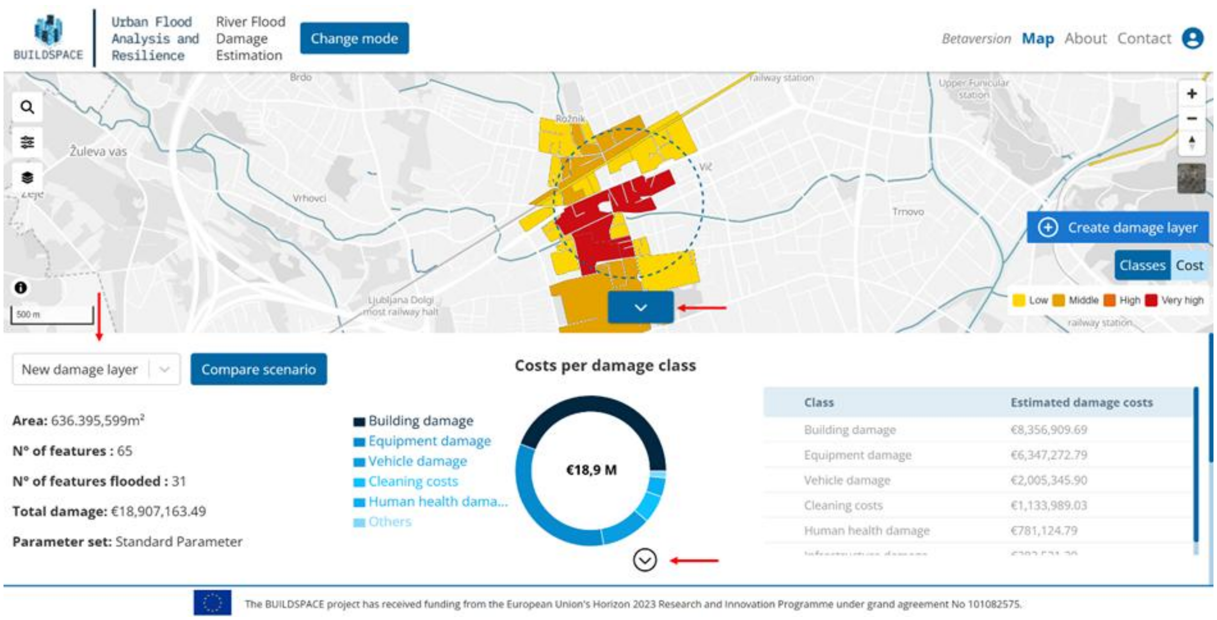


Figure 116. SE5: Data panel to showcase the results

Lastly, two layers can be also compared. To activate the comparison mode, the data panel of one of the layers to compare needs to be opened. If it is possible to compare that layer with another layer, the 'Compare scenario' button will be active and can be clicked. If it is not possible to compare, the button will be greyed-out. For a comparison to be possible, two result layers within the same mode and within the same area of interest are needed. When user successfully starts a comparison, the screen will look like Figure 117.

When the comparison is started, the result layer started from will be considered 'Scenario 1' and will be already loaded in. For Scenario 2, user will need to select it in the little box on the left of the panel, using the dropdown menu. This menu will show all available layers. Scenario 1 will be shown on the left on the map and in the data panel, scenario 2 on the right. By using the switch icon (two arrows) in the box, user can switch the position of Scenario 1 and 2. The data panel will show the comparison graphs and tables for both result layers. On the map, a slider appears that can be used to move left or right over the map, showing scenario 1 on the left and scenario 2 on the right. The comparison mode can be exit by clicking the red button saying 'Cancel scenario comparison'.

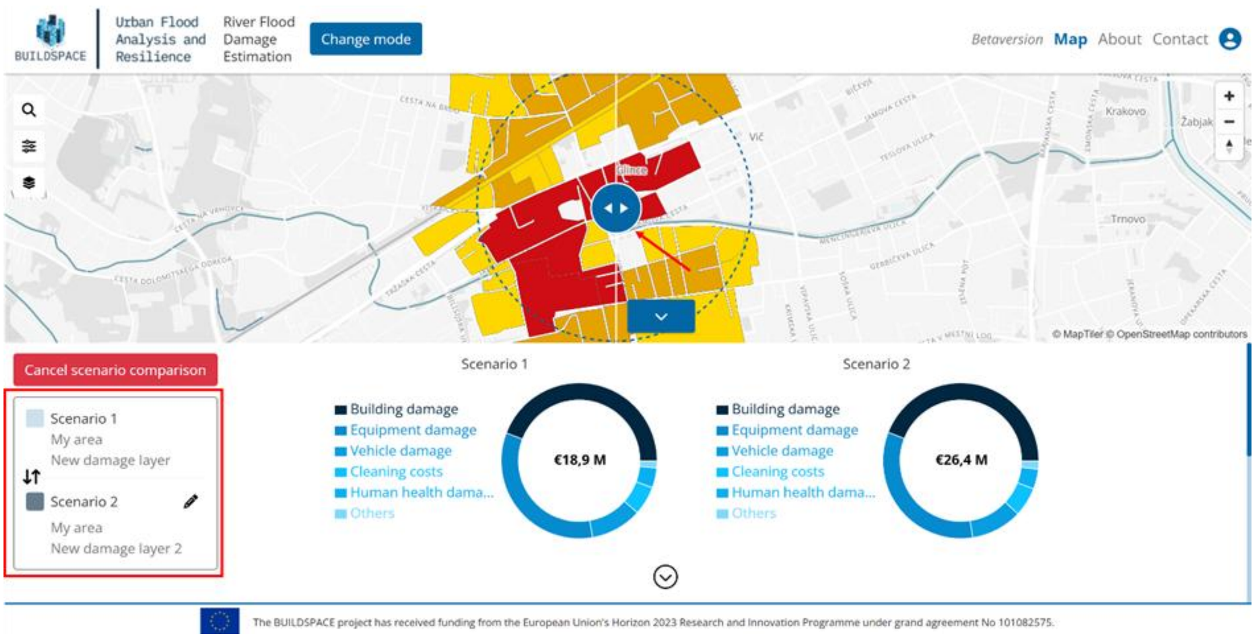


Figure 117. SE5: Comparing two layers

7.2.2.Target users and added value

SE5 supports a range of urban stakeholders involved in urban flood management. Table 17 summarises key user groups and the added value of the service for them.

Table 17. Added value of the SE5 service for different user types

User type	Added value of the SE5 Urban flood analysis and resilience
Public authorities and urban planners	- Identify urban flood risk hotspots to prioritise areas of intervention. - Simulates the impact of rainfall climate change on urban flood resilience using RCPs scenarios (RCP2.6/4.5/8.5) in three time-frames (2040/2070/2100). - Evaluates retrofitting strategies and future scenario resilience. - Provides urban runoff insights to support more effective spatial and water management including promoting BGI planning and implementing. - Facilitates evidence-based policy development and prioritisation of investments aligned with climate neutrality goals.
Researchers and consultants	- Offers a validated methodology combining building/land use typologies, simplified urban flood damage and runoff modelling, and localised climate projections. - Enables in-depth analysis of climate adaptation and mitigation scenarios at building and city scale. - Supports benchmarking, model calibration, and integration into broader urban energy system assessments.

Citizens and non-expert users	- Provides a simple, visual interface and user-friendly tool to explore building urban runoff performance and flood damage assessment in their neighbourhood. - Displays future urban floods trends at the building level. - Enhances public awareness and engagement in building renovation and climate adaptation. - Enhances public awareness in sustainability initiatives and implementation of blue-green infrastructure.

During testing, users recognized the application as a valuable professional tool for preparing spatial plans, planning civil protection measures, and informing design and engineering decisions. They especially emphasized the visual presentation of results and user-friendliness as key features for raising awareness and improving understanding and acceptance of BGI implementation among broader urban stakeholders.

7.3.Adaptation to pilots

SE5 was adapted to the specific needs of the Ljubljana pilot at the city scale. The pilot's main objective was to explore how data-driven tools could support urban decision-making by identifying areas most vulnerable to urban flooding in terms of flood damage and urban runoff. In close collaboration with key stakeholders, service was configured using national administrative GIS data including building information derived from cadastral records and flood-prone areas, the national Flood Damage Assessment Methodology (FDAM), pilot-data based developed urban runoff calculation methodology and local rainfall RCP scenarios.

Pilot-specific modifications were implemented during development to improve the tool's relevance and accuracy. Specifically, the FDAM method has been adapted (simplified) to the capabilities of the on-line user-friendly visualisation tool and the data available, also considering European data availability. Furthermore, UAC was found appropriate as a basis for the service's calculations for both the flood damage assessment as well as BGI impact via urban runoff simulations.

Preliminary pilot feedback confirmed achieving its objectives, showcasing the potential of city-scale services to promote informed decision-making and boost urban flood resilience. By identifying urban flood hotspots and visually assessing expected flood damage and urban runoff with BGI impact, there was recognised the added value of combining different data sources with SE5's key features, particularly with the scenario selecting and comparisons enabling with dynamically recalculated maps.

7.4.Technical developments – Final version

In this release, the focus of the technical developments was on two major elements. Firstly, the app was upgraded with a completely new second mode (already covered in the user experience in section 7.2): the urban runoff simulation. In this mode, user can simulate the effect of a 15-minute rainfall event on an area of interest. Based on the rainfall intensity, the characteristics of the soil as well as the implementation of possible BGI-measures, a runoff-value will be calculated for the whole area of interest as well as for each individual building. This allows policymakers to quickly estimate possible dangers and identify possible runoff hotspots.

Secondly, it was opted to increase the replication potential significantly. By using the Urban Atlas cover, which is available in over 700 European urban areas, a good first step was already taken. In this release, the focus was put on allowing the user to upload their own data to increase the replicability even more. A user can upload both detailed flood extent layers as well as their own building set layers. This effectively makes the application operational in every European city where the Urban Atlas is available and where the local authorities can provide flood extents or building datasets.

The application is still missing two elements which are planned to be released in the summer of 2025. Firstly, the upload functionality, both for flood extents and buildings, will be expanded to also link to the BUILDSPACE Core Platform. In this way, users can use data that is stored and made available on the core platform, either by their own organisations or by public entities. Secondly, the option to extract a report from a result layer will be added as well. This report will entail a screenshot of the map as well as all visualisations present in the layer panel including also the raw result data.

Finally, the application has been deployed on a public URL to be accessed by everyone. User only need to create an account by using the 'Sign up' link. The application can be accessed here: https://buildspace.nazkamapps.com/.

7.5.Replication and uptake potential

Service 5 has been constructed with the possibility of replication in mind. Therefore, it was decided to work with European datasets where possible to ensure maximum usability across the continent. Where European datasets are not available or insufficient, a basic upload functionality was foreseen. In this section, all the elements that have been taken to increase the replication will be explained.

7.5.1.Urban Atlas Cover and custom parameter sets

Service 5 uses the Urban Atlas Cover (UAC) as a base layer to calculate the result layer both in the river flood damage mode as well as in the flash flood hotspot simulation mode. The Urban Atlas Cover is a Copernicus land cover product that provides a classification of 17 urban classes and 10 rural classes for 788 urban areas of at least 50.000 inhabitants in Europe. The UAC is available in the following countries, as shown on the map in Figure 118:

- All 27 EU member states, including oversea areas such as La Réunion, Martinique, the Azores, Madeira and the Canary Islands.
- The EFTA states Iceland, Norway and Switzerland. Liechtenstein does not have an urban area of at least 50.000 inhabitants and is thus excluded.
- States of the Western Balkans: Albania, Bosnia & Herzegovina, Kosovo, Montenegro, North Macedonia and Serbia.
- Türkiye
- United Kingdom

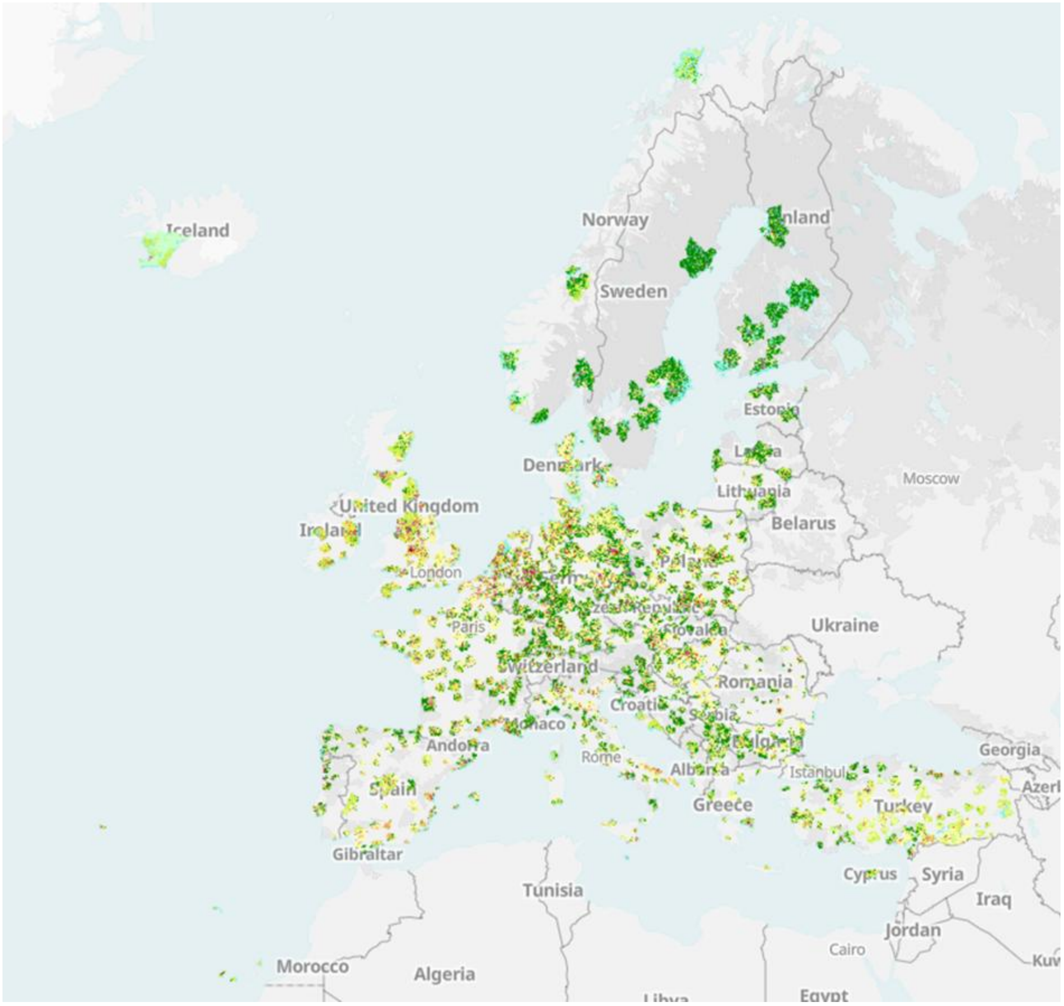


Figure 118. Coverage of the Urban Atlas Cover. Also included but not in frame: the French cities of Saint-Denis, La Réunion and Fort-de-France, Martinique.

In service 5, the UAC is used in both modes. In the mode 'River flood damage estimation', the UAC is used to estimate the total damage of a river flood. For each UAC class, a cost value per m² has been calculated based on the KRPAN methodology for Slovenia, for different damage classes. This value indicates what the damage cost would be if an area of 1 m² would flood for different damage classes. For example, for the UAC class 'Continuous urban fabric' a flood would cause €380 in damage to the infrastructure and €21 in vehicle damage, per square meter of flooded area.

In the flash flood hotspot simulation mode, an infiltration values are used to calculate the amount of water that would infiltrate and runoff during a precipitation event. The infiltration values are calibrated for each UAC class based on a soil parameter set. The soil parameter set simulates what the general soil characteristics are below the UAC surfaces and how this relates to the amount of water that will infiltrate. The application provides four general soil classes ranging from a high infiltration category such as sand soils to a very low infiltration category set such as clay soils.

All these values are now calibrated for Slovenia or use generalized values to get users started, but the application allows the users to change them for all UAC classes based on local variables and a more profound knowledge of the local area of interest. These so-called ‘parameter sets’ can be named and saved to the profile of the user. There the user can edit them again or delete them if they are not relevant anymore.

To create a new parameter set, the user can click the parameter button which is located at the top left part of the screen, below the search bar and above the layer selector. When clicked, all saved parameter sets to that profile will be listed. If there are no saved sets yet, the user can create a new set by clicking on the + symbol (Figure 119).

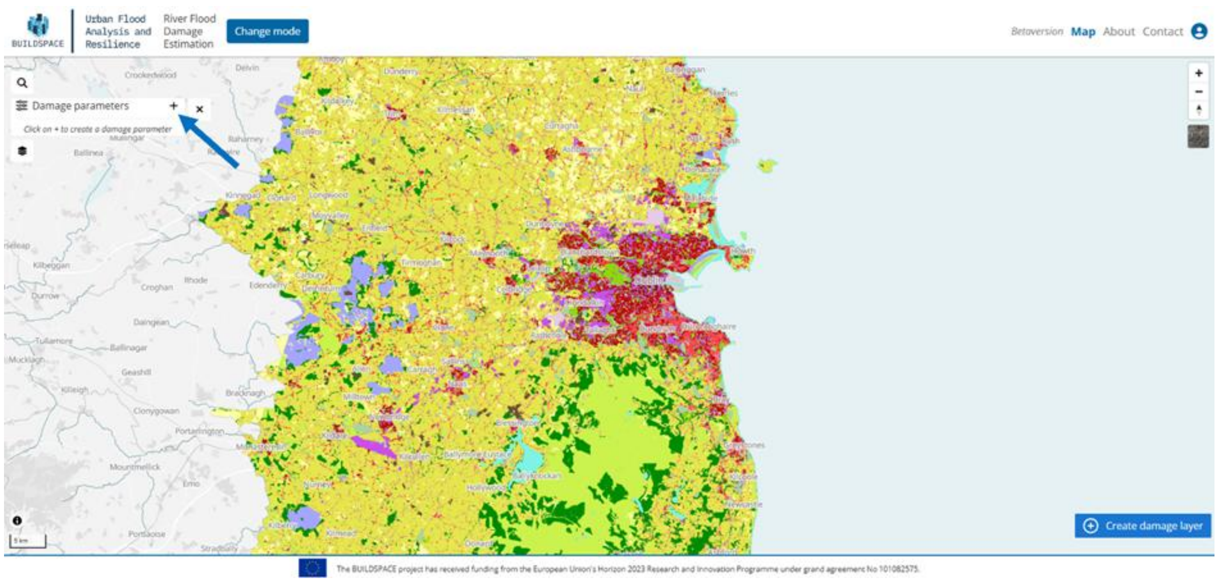
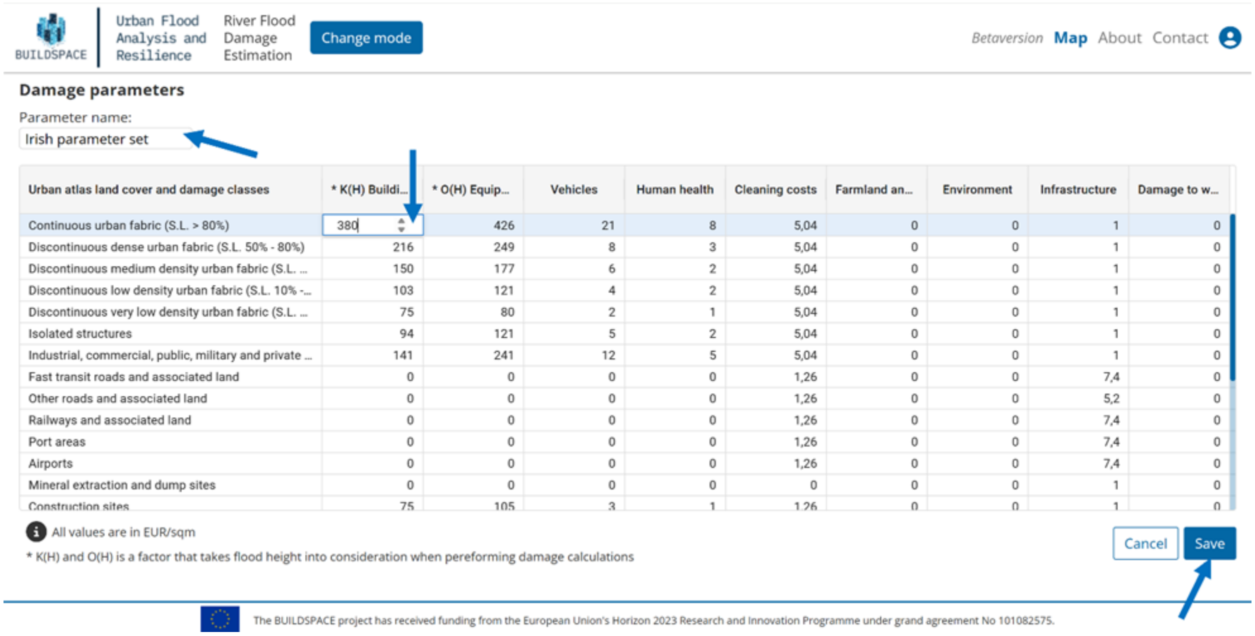


Figure 119. Creating a new parameter set

When creating a new parameter set or editing an existing one, the application will open a new view as can be seen in Figure 120. The screen will hold a table where the user can edit the parameter values for each UAC class. Depending on the mode the user is in, the table will differ in the number of parameters the user can change or the values that can be inputted. Above the table, the user can give a name to the parameter set using the text box. When the user is pleased with the changes, he can save the parameter set to his profile.



Urban atlas land cover and damage classes	* K(H) Buildi...	* O(H) Equip...	Vehicles	Human health	Cleaning costs	Farmland an...	Environment	Infrastructure	Damage to w...
Continuous urban fabric (S.L. > 80%)	380	426	21	8	5,04	0	0	1	0
Discontinuous dense urban fabric (S.L. 50% - 80%)	216	249	8	3	5,04	0	0	1	0
Discontinuous medium density urban fabric (S.L. ...	150	177	6	2	5,04	0	0	1	0
Discontinuous low density urban fabric (S.L. 10% -...	103	121	4	2	5,04	0	0	1	0
Discontinuous very low density urban fabric (S.L. ...	75	80	2	1	5,04	0	0	1	0
Isolated structures	94	121	5	2	5,04	0	0	1	0
Industrial, commercial, public, military and private ...	141	241	12	5	5,04	0	0	1	0
Fast transit roads and associated land	0	0	0	0	1,26	0	0	7,4	0
Other roads and associated land	0	0	0	0	1,26	0	0	5,2	0
Railways and associated land	0	0	0	0	1,26	0	0	7,4	0
Port areas	0	0	0	0	1,26	0	0	7,4	0
Airports	0	0	0	0	1,26	0	0	7,4	0
Mineral extraction and dump sites	0	0	0	0	0	0	0	1	0
Construction sites	75	105	3	1	1,26	0	0	1	0

Figure 120. Naming a parameter set and changing parameter values in the river flood damage estimation mode

When creating a new result layer, be it a river flood damage layer or a flash flood layer, the user has the possibility to choose which parameter set he wants to use. When clicking on the dropdown menu, the user can choose to use one of the standard parameters sets, or the custom parameter set they have created and saved to their profile. From this dropdown, it is also possible to click the option ‘Create a new parameter set’, which will navigate the users to the screen shown before (Figure 121).

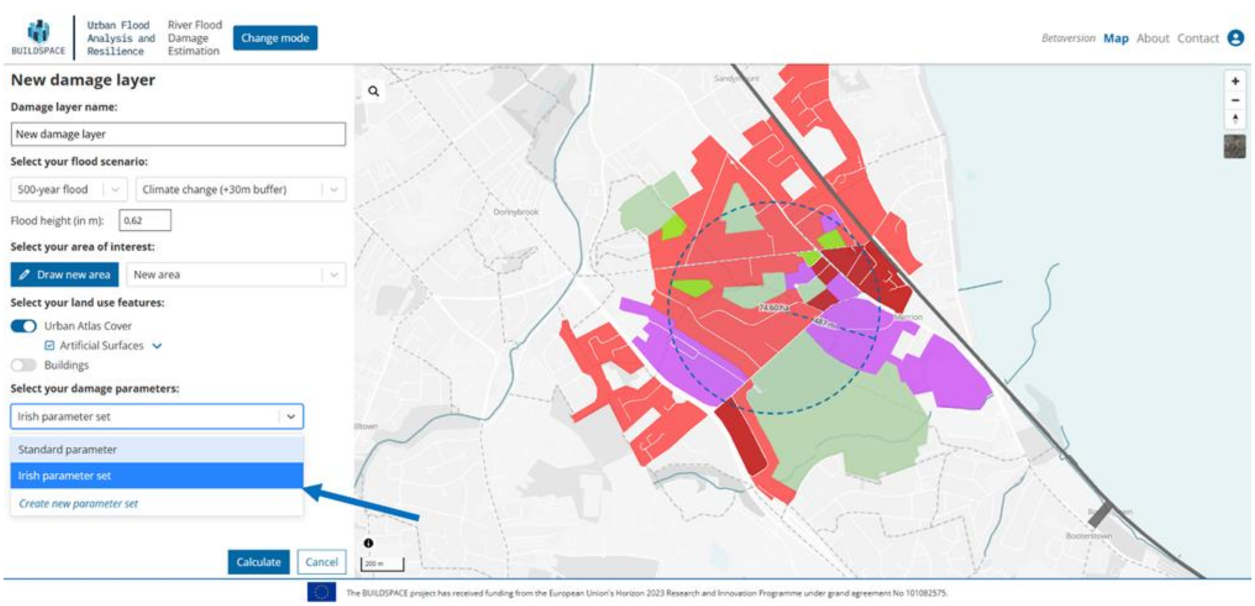


Figure 121. Selecting a custom parameter set when creating a result layer

7.5.2.Flood extents

In the river flood damage estimation mode, flood extents are a vital part of the calculations and it will not be possible to use this mode without a flood extent layer. The tool provides different flood extents based on predictions for the whole of Slovenia already. Outside Slovenia, users can decide to upload a flood extent they would like to use. For uploading, the user can upload a geojson file of maximum 5 MBs to use as a flood extent. The process is described in Figure 122. Next to the flood extents in the layer selector panel, there is an upload button. When clicked, a popup window will open where the user can choose to upload a file, either from their own device or from the BUILDSPACE Core Platform. The file the user wants to upload must be a geojson containing only (multi)polygons in the WGS 84 coordinate system with a maximum size of 5MB. Users are only allowed to upload three flood extent files.

When uploaded, the file will be added to the layer panel where the user can select it to visualise on the map. When creating a new damage layer, the custom floods will be added to the flood extent dropdown as extra options on the bottom. While the standard floods have the option to simulate climate change and anti-flood measures, this option does not exist for custom floods.

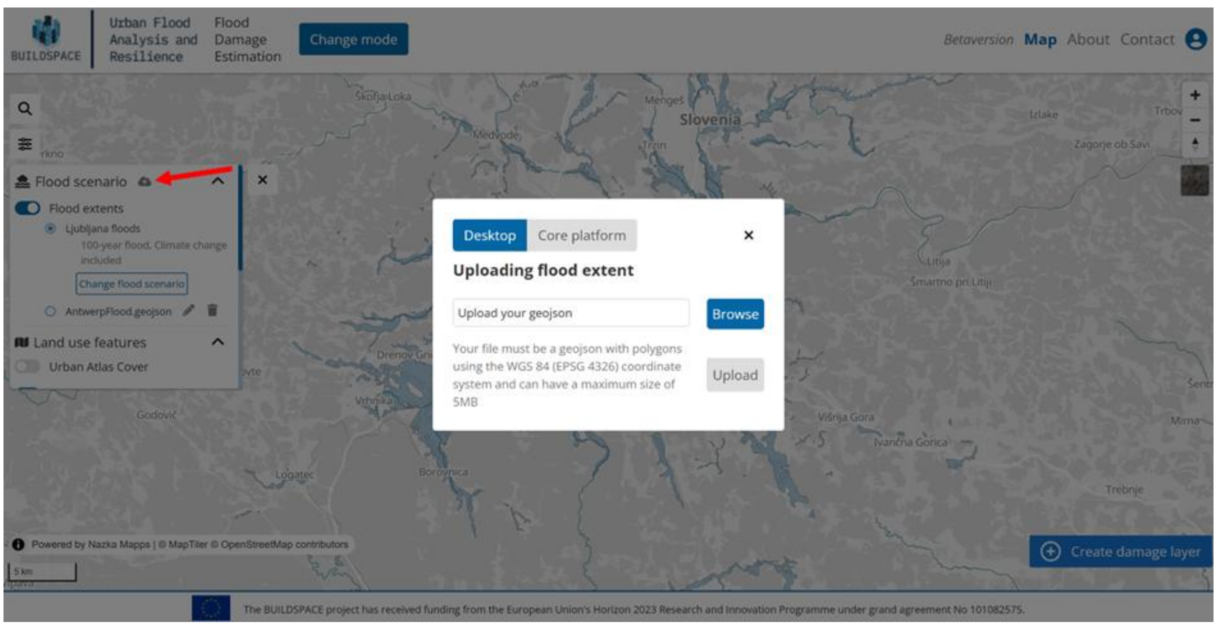


Figure 122. Uploading a flood extent

7.5.3.Building data

The application has a detailed file depicting the footprints of buildings in the Ljubljana Urban Region. In both modes, buildings are a handy addition to get more meaningful results, but they are not a necessity. It is possible to perform the calculations without buildings. To allow users outside of Ljubljana to extract information on a building level, the tool provides the option to upload a local building file in geojson format from the local device or from the BUILDSPACE Core Platform, as already explained in subsection 7.2.1.2. The geojson is limited in size to 5 MB to make sure that the application keeps running smoothly.

To upload a building file, a user can click the upload icon next to the building toggle in the layer selector. This will open a popup window as can be seen in Figure 123. In this popup, there is a toggle on top that will allow user to choose to upload from their own device or via the Core Platform.

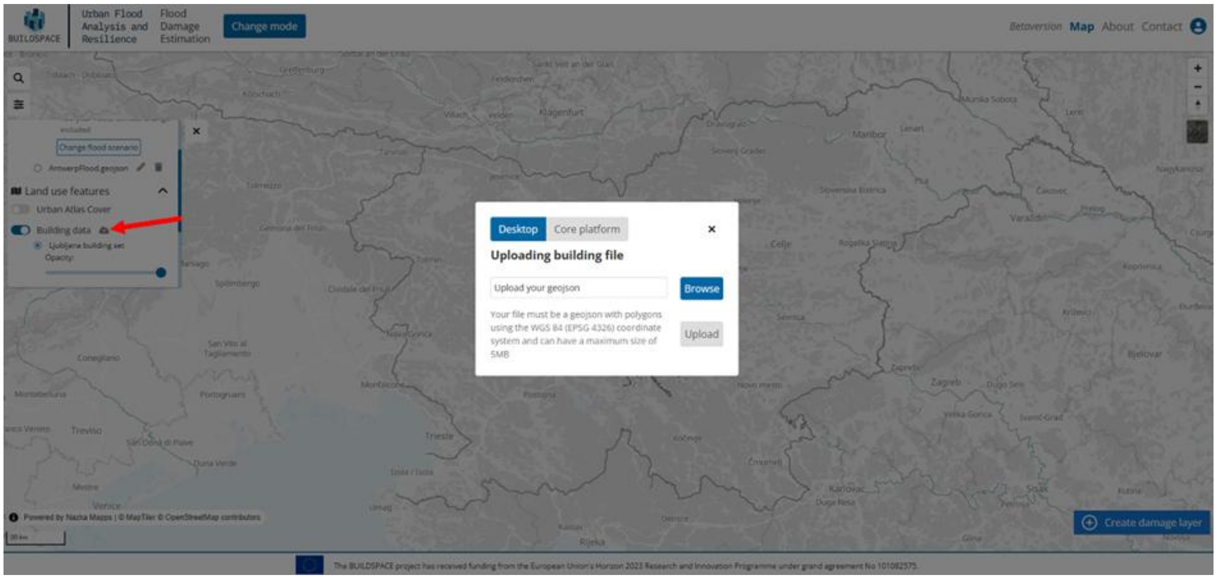


Figure 123. Uploading building data

7.5.4.Background layers

To help the user in navigation and orientation, the application includes some helpful background layers that can be found and toggled in the upper right corner. By clicking this toggle, two options appear for the user. Firstly, there is the possibility to activate a detailed global satellite layer. Further, a user can activate the 'Local boundaries' and select a country from the list. For most European countries, the application provides local administrative divisions. Depending on the country, these might be just regions or provinces all the way up to local municipalities. This functionality can be seen in Figure 124.

Figure 124. Local boundaries as navigation aid

8. Lessons learned and recommendations

The implementation of WP3 in BUILDSPACE, encompassing the design, development, and validation of the core platform and five services, has led to a number of key insights that will **inform future development, replication, and exploitation**. These reflections are drawn from the **technical challenges addressed**, the **synergies created** between services, and the broader perspective of **enabling scalable, interoperable and impactful digital solutions for climate-resilient and energy-efficient cities**.

A central lesson has been the value of **modularity in system architecture**. The development of a modular core platform, with well-defined APIs, authentication mechanisms and dataset management tools, allowed each service to evolve independently while maintaining integration within a unified ecosystem. This architecture not only facilitated collaborative development across partners but also ensured scalability for future replication and commercialisation.

The **integration of Copernicus core services (C3S, CLMS)** and Galileo-based EGNSS data brought important benefits in terms of scientific robustness, spatial accuracy, and policy relevance. These services enhanced the quality and reliability of the city-scale applications (SE3 to SE5) and supported precise geolocation in the building-scale services (SE1, SE2). However, this integration also posed technical challenges, especially regarding harmonisation of data formats, processing pipelines and user access. Addressing these challenges required substantial backend work and highlighted the importance of early-stage planning for data architecture.

Another important takeaway was the strength of **synergies between services**. While each addresses a distinct domain, from energy demand to flood risk or digital twin enrichment, many share data or workflows. For example, SE3 intersects meaningfully with SE4's heat risk mapping; and city-level services (SE3 to SE5) share climate projection pipelines. These connections increase the overall coherence and impact of the platform and suggest future exploitation could benefit from bundling services into thematic solutions.

Technical development also required addressing demanding tasks, such as processing high-resolution data, ensuring platform performance, and aligning heterogeneous inputs (e.g., BIM, IoT, remote sensing). The incremental release strategy adopted in WP3 was effective, allowing progressive validation and adaptation to pilot contexts.

Finally, the services developed under WP3 demonstrate **strong potential for replication and exploitation**. Their alignment with EU policy goals, reliance on authoritative open data, and capacity to operate across scales all support broader uptake. The co-creation process with pilot partners ensured the tools are not only technically sound, but also relevant and user-oriented.

In conclusion, WP3 has laid a robust foundation for BUILDSPACE's legacy. By combining technical innovation with strong user alignment and European data infrastructures, it offers a replicable model for smart, data-driven planning tools that support the climate and energy transition in urban environments.

9. Conclusions

This final deliverable of WP3 presents the complete development cycle of the BUILDSPACE core platform and its five services, reaching full maturity through the third and final technology release. The outcomes of WP3 confirm the feasibility and added value of combining remote sensing, geospatial intelligence, and advanced visualisation technologies to address key urban challenges related to energy efficiency, climate adaptation, and risk resilience.

Over the course of the project, the platform has evolved into a robust, modular, and user-friendly environment. It enables seamless integration of Copernicus and EGNSS data, as well as building-level and city-scale analytics. The services developed, which range from digital twin generation to climate scenario modelling, urban heat risk analysis, and flood resilience planning, have been successfully customised, deployed, and validated in diverse European pilot contexts.

A key achievement of WP3 lies in demonstrating the complementarity between the services. Each service delivers standalone value but can also be combined with others to support more holistic decision-making. Their interoperability, shared data infrastructure, and common interface design contribute to a cohesive ecosystem of tools that can be adapted to different user profiles and city needs.

The co-creation and testing process with pilot partners and stakeholders played a central role in aligning technical developments with real-world requirements. This user-centred approach has ensured that the resulting platform and services are not only technically advanced but also practical, policy-relevant, and ready for wider uptake.

In conclusion, WP3 has delivered an integrated digital platform and service suite that supports the Green Deal objectives by fostering data-driven planning, climate resilience, and sustainable urban development. Its outcomes serve as a foundation for future replication, scaling, and exploitation beyond the project’s lifetime.